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FINAL REPORT

FUEL PIN DESIGN, FABRICATION, AND FABRICATION EVALUATION [redacted]

by

H. W. Hill

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NUCLEAR TECHNOLOGY DEPARTMENT
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[redacted] GROUP [redacted] ~~rading and declassification~~ [redacted]

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FUEL PIN DESIGN, FABRICATION, AND FABRICATION EVALUATION

by H. W. Hill

I. ABSTRACT

Designs were developed to utilize TZM, W-25 Re, and W-30 Re-30 Mo cladding with either bulk or cermet UO_2 fuel in fuel pins capable of being operated at a maximum heat flux of 2 kW/in^2, clad surface temperature of 2500°F, and burnup of 5×10^{20} fuel atoms per cubic centimeter of pin. Techniques were developed to fabricate small fuel pins containing thin-wall, annular UO_2 pellets clad in TZM. Four prototype TZM-clad fuel pins were produced to demonstrate the fabrication techniques and inspection procedures. Six TZM-clad fuel pins containing enriched UO_2, suitable for irradiation testing at the desired operating conditions, were produced and examined. Techniques also were developed to fabricate prototype and irradiation pins with W-25 Re cladding. However, because the purchased W-25 Re cladding material did not meet specified compositional tolerances, no fuel pins were fabricated with this cladding material.

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II. INTRODUCTION

In response to technical and operational objectives enunciated by NASA for high temperature, gas cooled, nuclear reactor fuels, a technical brief was prepared by the Vallecitos Laboratory group during March, 1966. In this brief, the properties of candidate cladding materials and types of UO_2 fuel were reviewed in terms of their usefulness for fuel rods in a gas cooled core operating at high temperature. An irradiation program was suggested that would evaluate three candidate cladding materials and study parametrically the effect of varying the cladding thickness and fuel diameter. In a supporting laboratory research and development program, stress simulation tests were suggested for the candidate cladding at contemplated fuel surface temperatures and internal pressures resulting from fission gas release. These tests would provide the design basis for the fuel pins that would undergo irradiation testing and post-irradiation testing.

This report describes the work performed for NASA-Lewis Research Center on the design, evaluation, and fabrication of a group of fuel pins to be irradiated under conditions similar to those of the fuel in a High Temperature Gas Cooled Reactor which was in the conceptual stage of development at NASA. The RFP for this program was issued by NASA in mid-May, 1966, with a period of two weeks provided for proposal submittal. Selection of a contractor for the program was made by the middle of June and contract agreement completed by the end of the month.

III. FUEL PIN DESIGN

The first task in the program required the preparation of at least two fuel pin designs capable of operating with inert gas cooling at

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the following conditions:

Wall temperature	2300-2700°F
Surface heat flux	1.0-2.0 kW/in^2
Peak burnup	5×10^{20} atoms/cc

On the burnup requirements, the unit volume includes cladding, fuel matrix material, and central cavity when present.

The following criteria were also specified for the fuel pin designs:

Fuel material	UO_2
Length of fuel	2.00 ±0.01 inches
Fuel pellet o.d.	0.20 inches
Total length of fuel pin	minimum 3.25 ± 0.05 inches
	maximum 5.00 ± 0.05 inches

The ratio of the volume of the section of the pin containing fuel to the void volume (plenum plus central hole) was to be the same as that required for a fuel rod with a 30-inch fuel section that operated with a cosine power distribution with a peak heat flux of 2.0 kW/in^2.

Fuel pin designs were developed that were based on bulk UO_2 and a UO_2-refractory metal cermet. The experience of the Nucleonics Laboratory at Vallecitos was utilized for the bulk oxide fuel pin design and that of the Nuclear Materials and Propulsion Operation (NMPO-Cincinnati) for the cermet type fuel pin. Cladding considerations and design for both types of fuel pins were based to a large extent on the results of experimental programs done at NMPO. Some properties of the refractory materials recommended for the cladding were still under active study at NMPO when the fuel pin designs were made and when property data on other potential cladding materials requested by NASA were subsequently furnished to them.

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In those instances that the properties were still be investigated, the available data were used with a good deal of conservatism.

The fuel pin designs proposed for both bulk oxide and cermet fuels are considered in APED-5040, "Report No. 1, Proposed Fuel Pin Designs," a Classified (Confidential) report. Parametric studies were made on the factors that affect fuel and cladding life to provide a basis for selecting the wall thickness of the cladding and, in the case of the bulk oxide fuel, the length of the plenum void space required to permit the fission gases to be accommodated within permissible stresses in the cladding material.

The recommended design for the cermet fuel pin given in APED-5040 would use a W-15 UO_2 matrix with W-30 Mo-30 Re cladding or a Mo-14 UO_2 matrix with a Mo-TZM cladding. The fuel pin design and operating parameters would then be as follows:

Fuel Pin Design	(inches)
Fuel pellet, o.d.	0.200 ± 0.001
Fuel pellet, length	2.00 ± 0.01
Cladding thickness	0.010 ± 0.001
Cladding, o.d.	0.220 ± 0.002
Overall length of pin	3.25 ± 0.05

Operating Parameters	Minimum	Maximum
Heat Flux	1.0 kW/in^2	2.0 kW/in^2
Cladding Temperature, ^oF	2300	2700
Matrix centerline Temp, ^oF	2475	3055
Burnup rate f/cm^3-hr	1.56×10^{17}	3.13×10^{17}
Average thermal flux required n/cm^2-sec	2.26×10^{13}	4.51×10^{13}
Lifetime at indicated burnup rate, hrs	3525	1762
Lifetime fission density, fissions/cm^3	5×10^{20}	5×10^{20}

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Detailed consideration and calculations were made to obtain the diametral growth of both W-14 UO_2 and Mo-15 UO_2 cermets at the minimum and maximum operating conditions. It was concluded from these studies that the W-15 UO_2 cermet could achieve the design goal under both the minimum and the maximum operating conditions. With the Mo-14 UO_2 cermet, the design goal could be reached when operating at minimum conditions. The expected diametral growth of 6% when operating at maximum conditions, however, would probably result in failure as a result of cladding cracking and the release of fission products.

The fuel pin design for which bulk UO_2 is the fuel was developed with the same cladding materials, W-30 Re-30 Mo and Mo-TZM, that had been used as the reference material for the cermet fuel. The design was predicated on the ability of the cladding to withstand an external pressure of 1000 psig when the internal pressure was 0 psig. Further, the creep collapse of the cladding was to be minimized by reducing the cladding stresses to a point at which the creep would not exceed 5%. In addition, creep collapse would also be minimized by using an internal sleeve as a support for the cladding in the plenum region. The fuel itself was considered to provide support for the cladding along the fueled section of the pin. In developing this design for bulk UO_2 fuel, the requirement was imposed that the cladding would be able to withstand an internal pressure throughout its operating life equivalent to that produced by complete fission gas release at the end of life. It was recognized that this design basis was conservative, particularly when a normal external pressure of one atmosphere instead of the working pressure of 1000 psig was assumed to be exerted on the cladding in developing its thickness requirement to withstand the fission gas pressure.

Three types of UO_2 fuel design were presented for the two cladding materials. In the first type, the UO_2 had a small central hole, and

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the fuel would operate with approximately 65 % of the core in the molten state. In one variation of this type, the minimum cladding thickness would be used to give the maximum plenum length consistent with the overall fuel pin length (5 inch) limitation. A second variation would use a thicker cladding with the minimum permissible plenum length.

In the second type of UO_2 fuel design, a thin annulus of fully enriched, high density UO_2 fuel would be used to produce the desired operating conditions. An internal tungsten sleeve would provide support to the fuel and prevent fuel relocation from mechanical causes or plastic deformation. During operation, the fuel temperature would be well below the melting point of UO_2. The large central cavity introduces a void volume for accommodating the released fission gases and thereby reduces the length of plenum required for this purpose.

The third fuel design had a central hole whose size was such that the fuel temperature remained just below the UO_2 melting point. An internal tungsten sleeve was not considered feasible because of the small size of the central hole. Under these circumstances, fuel cracking and relocation was a possibility. For this reason and because of the small free volume that was made available, this design primarily served as an alternate for the first type in the event that operation with molten fuel could not be accepted.

Details of the two types of the first fuel pin designs with bulk UO_2 developed after extensive parametric analysis are shown in Table 1.

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TABLE 1. Fuel Pin Designs

Type I Fuel Pin Design

Cladding Material	Mo-TZM (inch)		W-30 Re-30 Mo (inch)	
Wall thickness	0.027	0.050	0.040	0.050
Cladding i.d.	0.202	0.202	0.202	0.201
Pellet o.d.	0.200	0.200	0.200	0.200
Pellet i.d.	0.040	0.040	0.040	0.040
Plenum length	2.25	1.3	2.25	2.2
Plenum sleeve, thickness	0.020	0.020	0.020	0.020
Fuel Pin length	5.0	4.05	5.0	4.95

Type II Fuel Pin Design

Cladding Material	Mo-TZM (inch)		W-30 Re-30 Mo (inch)	
Wall thickness	0.050	0.050	0.050	0.050
Cladding i.d.	0.202	0.202	0.202	0.202
Pellet o.d.	0.200	0.200	0.200	0.200
Pellet i.d.	0.160	0.120	0.160	0.120
Plenum length	0	0.6	0.9	2.0
Plenum sleeve, thickness	0.020	0.020	0.020	0.020
Fuel Pin length	2.5(1)	3.10(1)	3.4	4.85

(1) Extension to be added to give minimum length - 3.25.

The Type I pin contained a 1/8" thick pellet of depleted UO_2 as an insulator at each end of the fuel column. Outside of the depleted UO_2 pellet in the Type I design and at the end of the fuel column in the Type II design, a 1/8" thick disc of rhenium was used to prevent flux peaking. The thermal effect of this type of flux perturbation can be severe in a short irradiation pin, because the fuel length is so

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small. The rhenium flux depressant disc was later removed from the design as directed by NASA to reduce the cost of materials.

Further details of the fuel pin designs are given in "Report No. 1, Proposed Fuel Pin Designs." The designs considered in that report were complete to the extent that it was feasible to make them so. Details of the end plug design were not available from NASA at the time the report was written, so it was not possible to provide a complete design nor one compatible with the fuel pin holding device. Likewise, an analysis could not be made to determine the possibility or extent of material mismatching, because the temperature and power profiles of the full scale fuel rods were not available.

In summary, the cladding designs that are incorporated in the bulk oxide and cermet fuel pin designs given on pages 2, 3, and 4 of this report are based, for the most part, on experimental work at the Nuclear Materials and Propulsion Operation (NMPO) of the Nuclear Technology Department. This group has been obtaining the physical properties of refractory metals and alloys at high temperature over an extended period of years. During the past five years, considerable work has also been done by them on the design and fabrication of cermet fuels similar to the type discussed earlier in this report. This work at NMPO included irradiation testing of tungsten base alloys-UO_2 cermet fuel clad in the alloy used for the cermet at elevated temperatures (3600°F) for periods of more than 1,000 hours. The bulk oxide fuel pin designs were developed by the Nucleonics Laboratory of the Nuclear Technology Department on the basis of the background acquired during a comprehensive, high performance fuel irradiation program with bulk UO_2 as the fuel. In this program, fuel rods with a 30-inch section of UO_2 fuel were irradiated to burnups of more than 5×10^{20} fissions/cc at surface heat fluxes near 3 kW/in^2. This background of design, fabrication

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and irradiation experience with the two types of fuel suggested for the fuel pin designs provided excellent likelihood that the fuel pins developed in this program would achieve target irradiation objectives.

In response to a NASA request (September, 1966) a compilation was made of the properties of potential cladding materials for the bulk UO_2 fuel concept other than the TZM and W-30 Re-30 Mo suggested in APED-5040. It was hoped that this compilation, which included the pure metals and one other tungsten base alloy, would provide cladding materials superior to the ones suggested. The information compiled is given in Table 2 and serves to supplement Table 4 of Report No. 1.

After the design report had been submitted (August, 1966), the contractor was notified by NASA (November, 1966) that the fuel pin design would utilize only bulk UO_2 as the fuel. The UO_2 fuel pellets specified were to be similar to Type I described previously in this report with a 0.040" central cavity and Type II with a 0.110" central cavity; i.e., 0.045" wall thickness. The cladding materials selected by NASA at this time were Mo-TZM and W-25 Re. Fuel pins with Mo-TZM cladding would contain Type I fuel. Two sets of fuel pins were to be made with the W-25 Re cladding, one with Type I fuel and the other with Type II. The fuel for the Mo-TZM cladding was subsequently changed (December, 1966) from Type I to Type II, and the wall thickness of the Type II fuel pellets was reduced (January, 1967) from 0.045" to 0.040". An end closure design for the fuel pin was developed (November, 1966) in accordance with NASA direction. The closure contained a thermocouple well and a thermocouple guard tube. Dimensions were established in the end plug to assure complete weld penetration when electron beam welding was used to make the cladding-end plug closure.

The plenum length in the several types of fuel pins underwent several

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TABLE 2. Properties of Potential Cladding Materials at 2500°F

Material	W Arc Cast	W Powder Met.	W-25 Re Powder Met.	W-30 Re-30 Mo Powder Met.	Mo Arc Cast	Mo-TZM Arc Cast
Modulus of Elasticity (psi)	30×10^6	29.5×10^6 (10)	30×10^6 (4)	25×10^6 (4)	8×10^6 (2)	25×10^6 (1)
Yield Strength (psi)	10,000 (10)	5,000 (10)	80,000 (12)	50,000 (3)	3,000 (2)	15,000 (2)
Tensile Strength (psi)	25,000 (10)	15,000 (10)	120,000 (12)	60,000 (3)	12,000 (2)	25,000 (2)
Poisson's Ratio	0.3 (4)	0.3 (4)	0.3 (4)	0.3 (4)	0.3 (4)	0.3 (4)
Coeff. Thermal Expansion (in/in-°F)	3×10^{-6} (1)	3×10^{-6} (1)	2.9×10^{-6} (5)	3.2×10^{-6} (5)	3.6×10^{-6} (1)	3.5×10^{-6} (1)
Thermal Conductivity (Btu/h-ft-°F)	58 (1)	58 (1)	53 (4)	43 (5)	40 (1)	50 (1)
Stress to Rupture (psi)						
1,000 hr	5,600 (8)	4,800 (8)	5,000 (8)	3,500 (8)	1,600 (9)	5,500 (8)
4,000 hr	4,500 (8)	3,000 (8)	4,000 (8)	3,000 (8)	1,200 (9)	3,000 (8)
Creep Rate at 5000 psi in/in-hr	- - -	2×10^{-6} (13)	5×10^{-6} (13)	5×10^{-4} (7) 1.5×10^{-5} (7) (at 2500 psi)	- - -	1.5×10^{-5} (11) 1.5×10^{-6} (6)

1. Personal communication. R. Eckart. GE-NMPO.
2. DMIC RPT-190, pp A-19, A-19, A-21, A-212.
3. GEMP-400A, p. 55.
4. Assumed value.
5. Personal communication. C. Tarr. GE-NMPO.
6. Power function estimate from data in DMIC RPT-190 (Table A-89).
7. Power function estimate from data in GEMP-59A, pp. 28-34 and TM-65-11-13, Table 3.
8. Estimated from Larson-Miller parameter in GEMP-400A, pp. 24, 53, 54.
9. Estimated from Larson-Miller parameter in GE-TM 65-4-39, p. 4.
10. DMIC RPT-191, pp. A-10, A-11, A-17.
11. Power function estimate from data in GEMP-400A (Fig. 2.5).
12. Personal communication. F. Hall. Hoskins Metals, Detroit, Michigan.
13. Power function estimate from data in DMIC-191 (Table A-12, A-13), pp. A-36 and A-37.

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perturbations from the original lengths recommended in Report No. 1. To obtain a shorter overall fuel pin length, the first plenum lengths requested by NASA (November, 1966) were markedly shorter than those recommended to the extent that insufficient volume possibly was being provided for the expected fission gas release. In subsequent discussions (January, 1967) on fuel pin design and materials procurement, agreement was reached to reduce the original plenum length to a smaller extent. Finally, the decision was made by NASA to use high temperature surveillance and rupture tests at the Lewis Research Center on samples of cladding to be used for the fuel pins as the basis for specifying the plenum length to be used. The plenum lengths in the Mo-TZM clad fuel pins with enriched UO_2 fuel were selected in this way. The same procedure was to be used in specifying the plenum lengths for the W-25 Re clad fuel pins at the time the technical effort on the program was stopped.

IV. UO_2 FUEL AND INSULATOR FABRICATION AND CHARACTERIZATION

Two different sintered UO_2 fuel shapes were employed in the fuel pin designs. The Type I fuel design utilized a thick-wall cylindrical shape with an o. d. of 0. 20 in. and an i. d. of 0. 040 in. The Type II fuel column was comprised of thin-wall shapes with o. d. and i. d. of 0. 20 and 0. 120 in., respectively. The depleted UO_2 insulators were cylindrical with a diameter of 0. 20 in. and a height of 0. 250 and 0. 125 in. for use with Type I and Type II fuel columns respectively. The thicker insulators were deemed necessary to contain the molten volume which will be present in the thick-wall fuel during irradiation. A pressing and sintering process was employed to make all UO_2 bodies; however, different fabrication techniques were used to produce the different shapes. Typical samples of the fabricated fuel shapes are shown in Figure 1.

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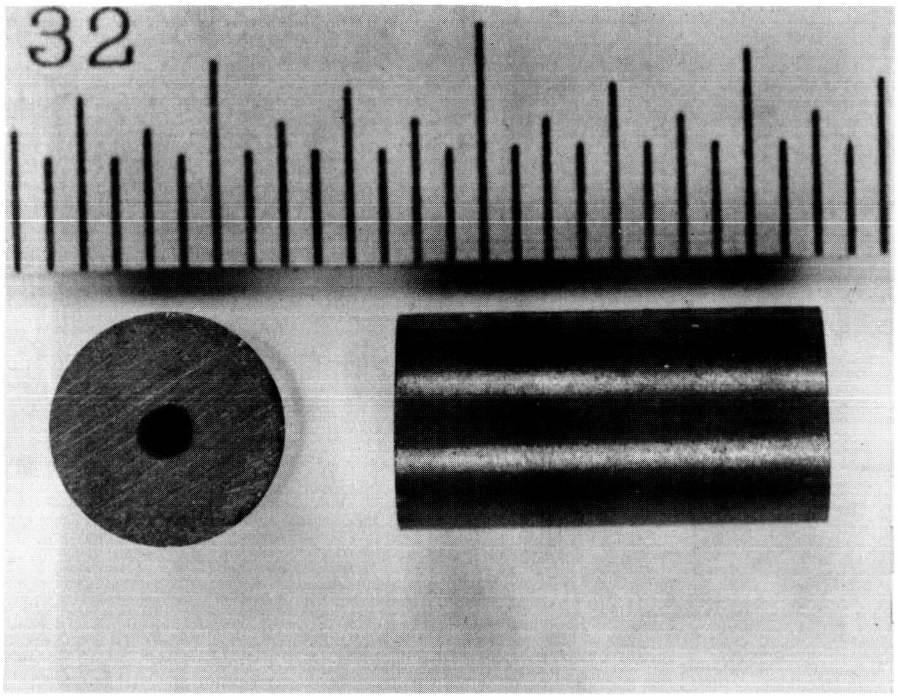
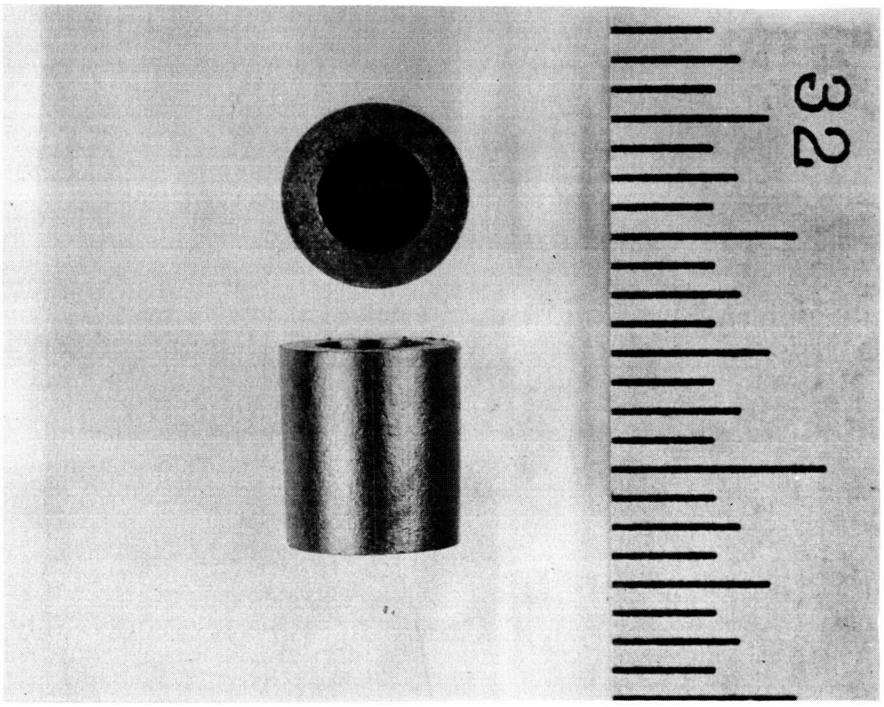


Type I

o.d. - 0.197 in.

i.d. - 0.040 in.



Type II

o.d. - 0.197 in.

i.d. - 0.120 in.

FIGURE 1. UO_2 FUEL SHAPES

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Ceramic grade UO_2 powder was procured from two vendors. UO_2 depleted in U-235 was supplied by Nuclear Fuel Services for insulators and prototype fuel fabrication, while United Nuclear provided UO_2 enriched to 93% in U-235 for the actual fuel pin fabrication. A characterization of the powders provided by the two vendors is shown in Table 3.

Type I fuel was fabricated by drilling a 0.040 in. hole in sintered UO_2 pellets made by the following procedure. The UO_2 powder first was pressed at 12,000 psi and then passed through a 20-mesh screen to effect a granulation with desirable properties for the final pressing. After 0.2 wt% Sterotex had been blended with the granulated powder to serve as a lubricant, the powder was loaded into a cylindrical die and pressed from two directions at 20,000 psi. Cylindrical pellets, with length/diameter ratios of about two, were formed in this manner. These pellets then were sintered at 1700°C for 6 hours in a hydrogen atmosphere. The dense pellets then were centerless ground to produce the desired o.d. and cored with a diamond drill to form the 0.040 in. i.d. If necessary, the lengths of the shapes were adjusted by grinding with SiC. After the machining operations had been completed, the fuel shapes were rinsed in distilled water and subjected to a second hydrogen firing. The shapes were heated at 1400°C for 6 hours in dry hydrogen (-80°F dew point) to effect a final cleaning and to adjust the O/U ratio to 2.00.

The UO_2 insulator shapes were fabricated in the same manner as Type I fuel. Solid cylindrical shapes were pressed, sintered, and centerless ground. These cylinders then were cut into shorter lengths with a diamond cut-off wheel. The 1400°C cleaning in dry hydrogen was again employed as the final process operation.

Type II fuel presented additional fabrication problems because of its small wall thickness. The 0.040 in. wall was too thin to be formed by

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TABLE 3. Characterization of UO_2

	Depleted UO_2 Powder	Depleted UO_2 Sintered Pellet	93% Enriched UO_2 Powder	93% Enriched Sintered Pellet
Al	40ppm	24 ppm	4 ppm	2
Sb	< 2	< 2	< 2	< 2
B	0.6	0.3	0.2	0.2
Bi	< 1	< 1	< 1	< 1
Cd	< 0.5	< 0.5	< 0.5	< 0.5
Ca	100	10	5	2
Cr	200	48	36	20
Co	< 2	< 2	< 2	< 2
Cu	20	5	1	1
Fe	600	66	34	20
Pb	25	1	1	1
Mg	50	4	2	2
Mn	25	2	1	1
Mo	< 3	5	< 3	< 3
Ni	100	12	16	8
Si	600	200	16	10
Ag	< 0.1	< 0.1	< 0.1	< 0.1
Na	< 15	< 15	< 15	< 15
Sn	2	2	1	1
V	< 11	< 11	< 11	< 11
Zn	40	< 10	< 10	< 10
Cl		< 3		< 3
F		2		2
C		5		6
O/U Ratio		2.010 ± 0.005		2.005 ±0.005
Bulk Density (g/cm^3)		10.42 ± 10.53		10.31 ±10.53
Bulk Density (% T.D.)		95.0 - 96.0		94.0 - 96.0

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drilling, unless extreme care was taken. Therefore, a procedure was developed to permit forming a pre-determined shape in the green state and then sintering the pressed compacts to the desired size and density. In the development program, the effect of processing parameters upon green pellet strength and integrity, sintered pellet density and integrity, and firing shrinkage uniformity were determined. Such parameters as granulation size, pre-pressing and forming pressures, die design, and sintering conditions were optimized to enable the pellet shape to be pressed and sintered directly to the final dimensions.

A fabrication process utilizing these optimized conditions was employed for all Type II fuel production. The ceramic grade UO_2 powder first was pressed at 12,000 psi and then granulated through a 20-mesh screen. After an addition of 0.2 wt% Sterotex had been blended with the UO_2, the powder was loaded into the die shown in Figure 2, Part 3. The fuel shape then was formed by two-directional pressing at 8000 psi. This procedure resulted in a formed shape of sufficient strength to be handled in the unfired state. A minimum of shrinkage non-uniformity also was achieved. After firing shrinkages of the depleted and enriched UO_2 were measured, dies were fabricated to permit sintering the shapes directly to final diameters with tolerances of ± 0.001 in. The 0.001 in. tolerance was desired in both Type I and Type II fuel to insure that differential thermal expansion will not result in a fuel-clad stress interaction and, at the same time, to minimize the fuel-clad gap during irradiation. All fuel was sintered at 1700°C for 6 hours in hydrogen. To produce the 2.00 in. fuel column length, the lengths of the individual sintered pellets were adjusted by grinding. This cold pressing and sintering process was found to result in about a 10% loss of pellets by breakage. All of the breakage occurred during pressing and handling. The sintering operation presented no problems. The broken pellets were reprocessed easily by granulating them and blending with the original UO_2 powder. The extent of this recycling

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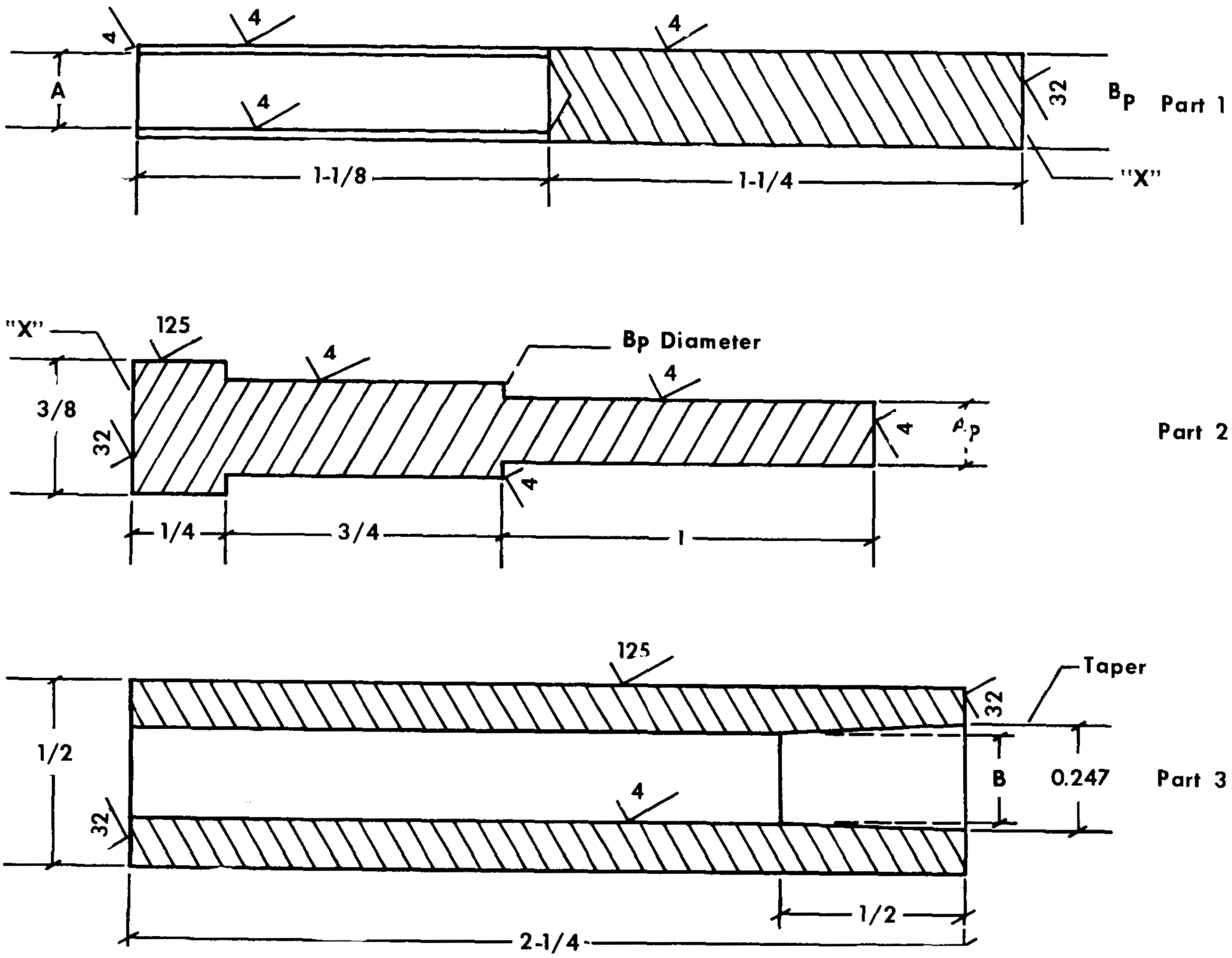

NOTES:

1. $A = 0.151 \pm 0.001$ Dia. $\qquad B = 0.244 \pm 0.001$ Dia.

   $A_P = A \begin{matrix} + 0.000 \\ - 0.001 \end{matrix}$ Dia. $\qquad B_P = B \begin{matrix} + 0.000 \\ - 0.001 \end{matrix}$ Dia.

   The diameter difference between A and A_P and B and B_P shall be less than 0.001 inch.

2. Materials for both punches and die shall be tool steel hardened to R/C 62-64.

3. Surfaces marked "X" and all mating surfaces shall be parallel and perpendicular to within 0.005 T.I.R. to each other when punches are in die.

4. Taper is to be a uniform 0.003 diameter increase.

FIGURE 2. DESIGN OF DIE FOR USE IN THIN-WALL UO_2 PELLET FABRICATION

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[redacted]

could undoubtedly be reduced substantially in a large scale operation.

It was necessary to perform shrinkage tests on the depleted and enriched lots of UO_2 before dies were chosen for the production of Type II fuel. Differences in the compacting and sintering behavior between the depleted UO_2 provided by Nuclear Fuel Services and the enriched UO_2 procured from United Nuclear resulted in comparative firing shrinkages of 19.4% and 21.2% respectively. It was necessary to fabricate dies of different dimensions to enable both the depleted and enriched fuel shapes to be sintered directly to the same size. It is anticipated that this shrinkage non-uniformity will present a problem to some extent from lot to lot of UO_2 of a particular enrichment provided by the same vendor. A very thorough blending of the lots provides a means to improve the uniformity during large volume production.

The fabricated UO_2 fuel and insulator shapes were characterized for impurity content, O/U ratio, density, and microstructure. These results are summarized in Table 3. Impurities were analyzed by emission spectrographic techniques. The O/U ratios were measured by thermogravimetric oxidation to U_3O_8. Densities were determined by bulk immersion techniques. Representative microstructures of the fabricated fuel and insulator shapes are shown in Figures 3 and 4. The polished sections of UO_2 were prepared for etching by attack polishing with a slurry containing 30% hydrogen peroxide and Linde-B alumina. Etching was accomplished with a solution containing one part of sulfuric acid (concentrated) and nine parts of hydrogen peroxide (30% concentration).

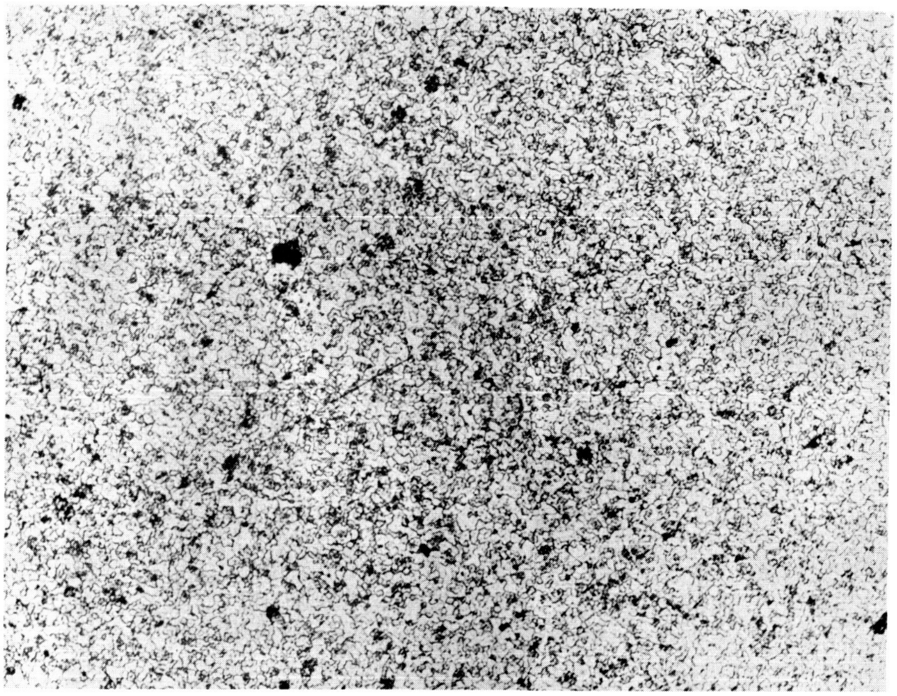
V. TZM FUEL PIN FABRICATION

A. Fabrication and Inspection Techniques

All TZM materials were procured from Climax Molybdenum

[redacted]

[redacted]



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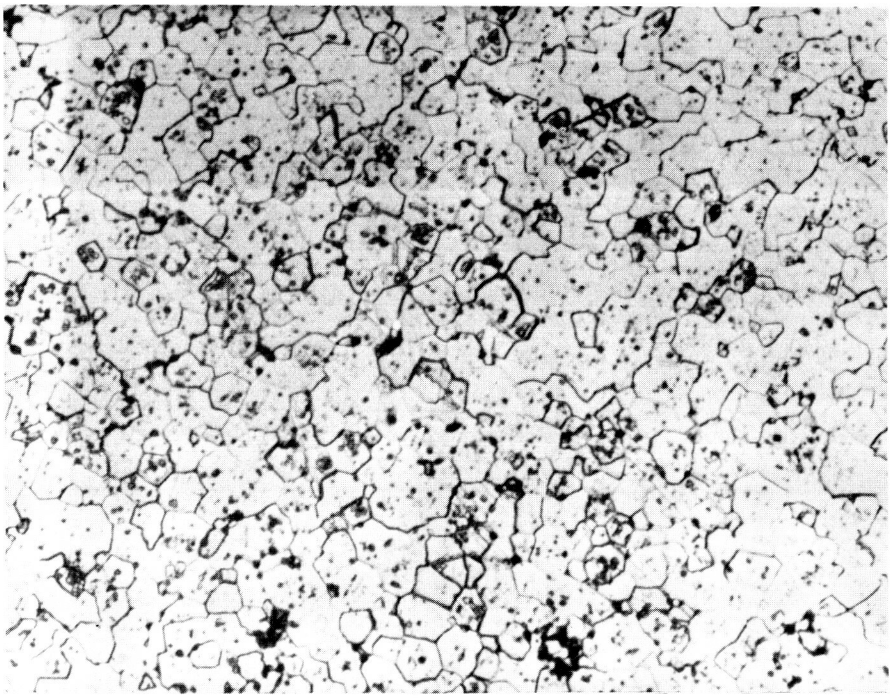

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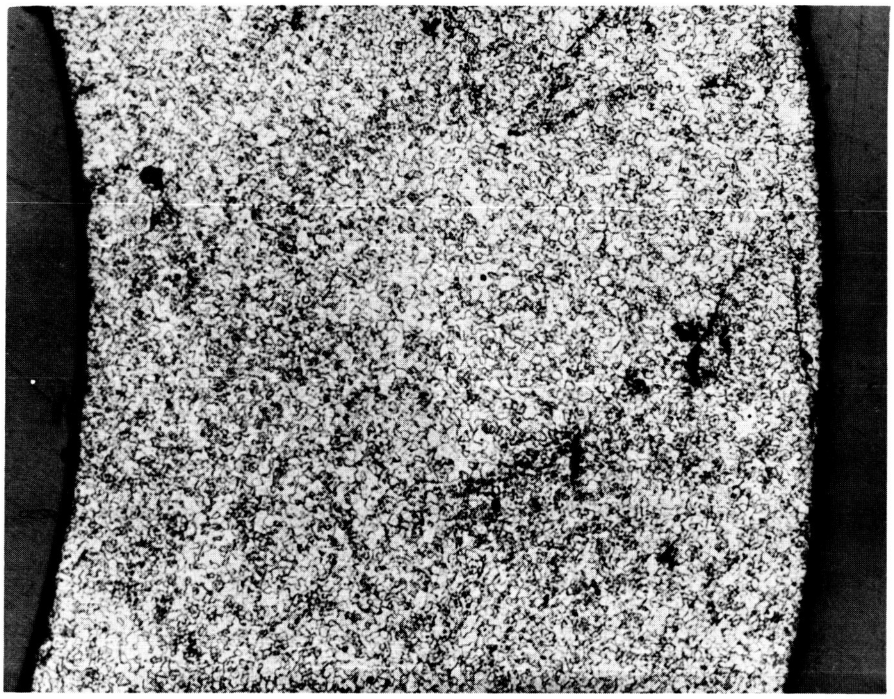
FIGURE 3. SINTERED DEPLETED UO_2 MICROSTRUCTURE. TYPICAL OF PROTOTYPE FUEL AND INSULATORS

[redacted]

[redacted]



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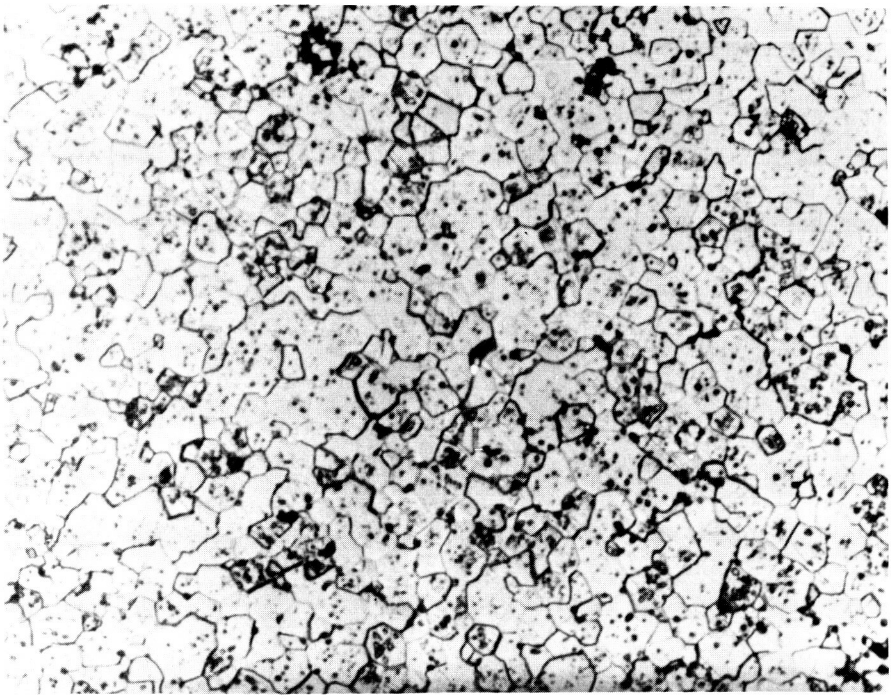

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FIGURE 4. SINTERED ENRICHED UO_2 MICROSTRUCTURE. TYPICAL OF FUEL FABRICATED FOR FUEL PINS

[redacted]

Company. Tubing, machined to the desired dimensions, was supplied for the cladding and plenum sleeve. Rod stock was provided for the end plug fabrication. Details of the Climax fabrication processes are described in Appendix A.

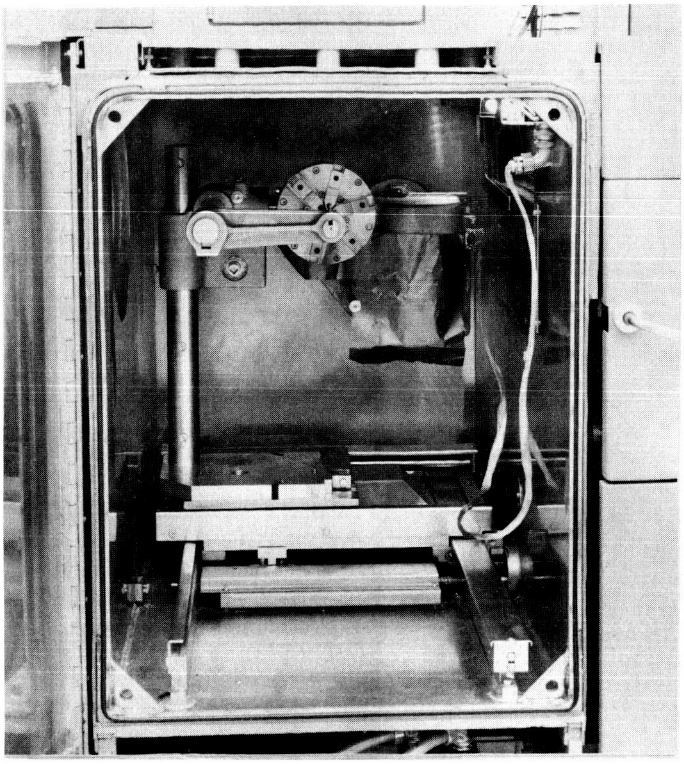
The end plug for all TZM fuel pins was integral in design, incorporating both the thermocouple guard tube and the end weld closure in one piece. This part was machined from rod stock. It was found that both conventional drilling and electrical discharge machining (EDM) could be used to drill the long thermocouple holes in the end plug; however, the former technique was used for end plug fabrication because of economic considerations. Standard drills were lengthened and were kept aligned to enable concentricity to be maintained while the long, small diameter holes were formed.

The only machining operation required for the cladding and plenum tubing was cutting the stock to the desired length. The tubing first was cut to approximate length with a silicon carbide cut-off wheel. Then it was mounted in a lathe and faced off accurately to the desired length. This technique was employed to assure that the cladding was cut at a 90° angle. This is important in maintaining a close fit with the end plug during welding. This procedure will result in a minimum weld zone and will maintain the concentricity of the end plug and the cladding.

After all TZM parts had been machined to the desired dimensions, they were cleaned to prepare them for welding and loading. The refractory metal parts first were immersed in an Oakite degreasing solution and alkaline cleaner. After rinsing in hot water, the metal parts were dipped in hydrochloric acid and then in a sulfuric-nitric acid solution.

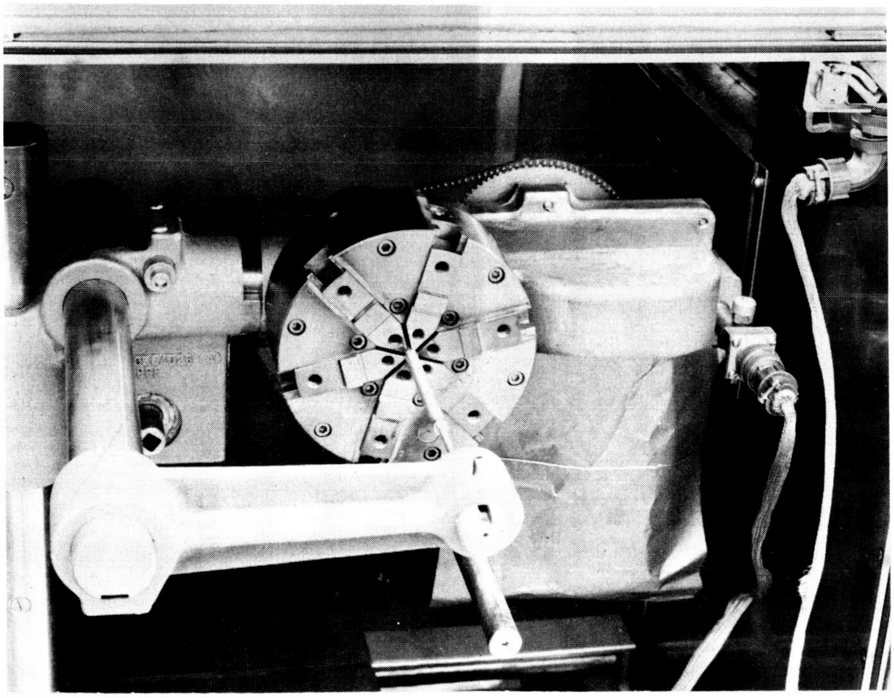
Successive immersion in two baths of deionized water, followed by two baths of methanol, was used to remove all traces of the cleaning solution. Finally, the TZM was fired for 30 minutes at 1100° in a dry hydrogen atmosphere. Wet hydrogen, normally used to assure carbon removal, was not employed in this instance because of the possibility of oxidation of the phase constituents of the alloy. The 0.001 inch thick tungsten fuel sleeve was subjected to the same chemical cleaning used for the TZM; however, the hydrogen firing was omitted to avoid recrystallization.

Electron beam welding was used to join all end plugs to the cladding. This welding technique was employed to assure weld penetration to a depth equal to the wall thickness of the cladding. During the handling and assembly of the TZM parts for welding, extreme care was exercised to keep them clean. The parts were handled only with nylon gloves until welds had been made at both ends of the fuel pins. To make the first weld, the end plug was inserted into the cladding until the shoulder of the end plug rested snugly against the end of the cladding. This assembly then was mounted in the positioning apparatus of the Hamilton Standard Electron Beam Welder (Model No. W2-36X23X30) as shown in Figure 5. The end of the plug was held tightly in position during welding by the special holder shown in the photograph. This holder was fitted to the configuration of the end plug. By maintaining a pressure contact of the cladding on the shoulder of the end plug during welding, the alignment between the two parts was held within tolerances. Concentricities with tolerances of less than 0.007 in. T.I.R. were held over the entire length of the fuel pin and end plug assembly. After the apparatus had been moved into position in the electron beam welder, the chamber was evacuated to $<1 \times 10^{-4}$ torr. The sample first was rotated under the electron beam with the beam



Vacuum Chamber

Components in Welding Position



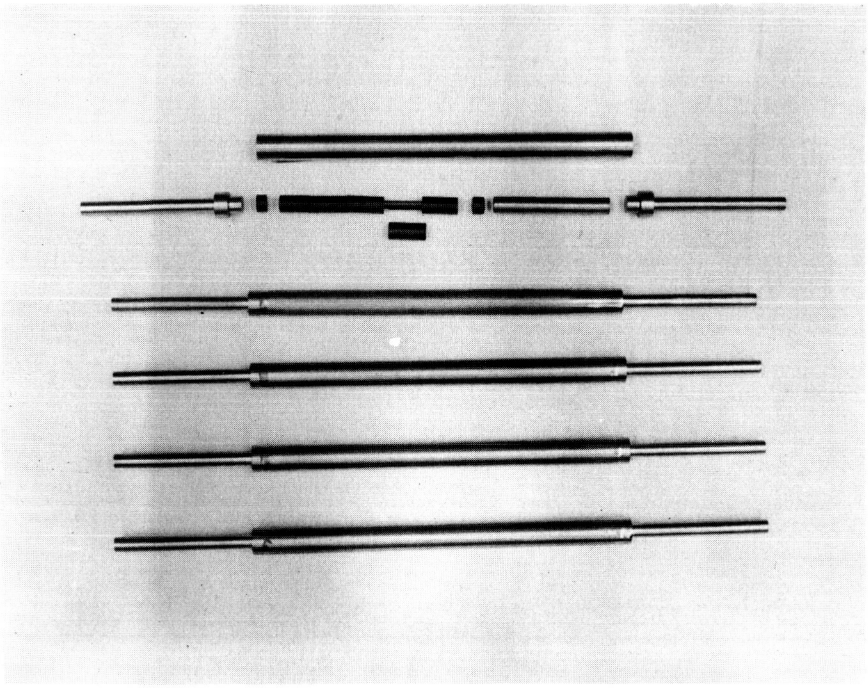
Detail of Positioning and Rotating Apparatus

FIGURE 5. HAMILTON STANDARD ELECTRON BEAM WELDER MODEL NO. W2-36X23X30, SHOWN WITH TZM CLADDING AND END PLUG IN POSITION FOR WELDING.

focused over a broad area of the weld zone. This served to preheat the sample to about 800-1000°C. Then the beam was focused to a small point, and the weld made by rotating the sample under the beam. The sample was allowed to cool to room temperature in the vacuum chamber after welding.

After the first end plug had been welded and checked for leaks with a helium mass spectrometer leak detector, the fuel pin components were assembled and loaded. The leak detection technique involved placing the open end of the cladding-end plug assembly over the inlet of the leak detector, evacuating the system, and introducing helium over the outside surfaces of the welded assembly. If the weld contained a leak, helium would enter the assembly and would be detected in the detecting system. The tungsten fuel sleeve was fabricated by bending the 0.001 in. foil around a 0.120 in. mandrel. The UO_2 pellets then were loaded onto the fuel sleeve. One depleted UO_2 insulator, the fuel column, the second depleted UO_2 insulator, and the plenum tube were loaded in that order into the cladding. The assembled components are shown in Figure 6. The second end plug was inserted into the cladding, and the loaded pin was positioned in the electron beam welder. The chamber was evacuated to $< 5 \times 10^{-5}$ torr for the final weld. The fuel pin was held in the vacuum chamber for about one-half hour to insure that the vacuum inside the pin would be near 5×10^{-5} torr before welding. After the second weld had been completed, the fuel pin was allowed to cool to room temperature and then was removed from the chamber.

The microstructure in a typical TZM weld region is shown in Figure 7. The polished sections were etched electrolytically in a solution containing 5% sodium hydroxide. The TZM in the weld has recrystallized. The weld can be seen to have penetrated



TZM and Fuel Components

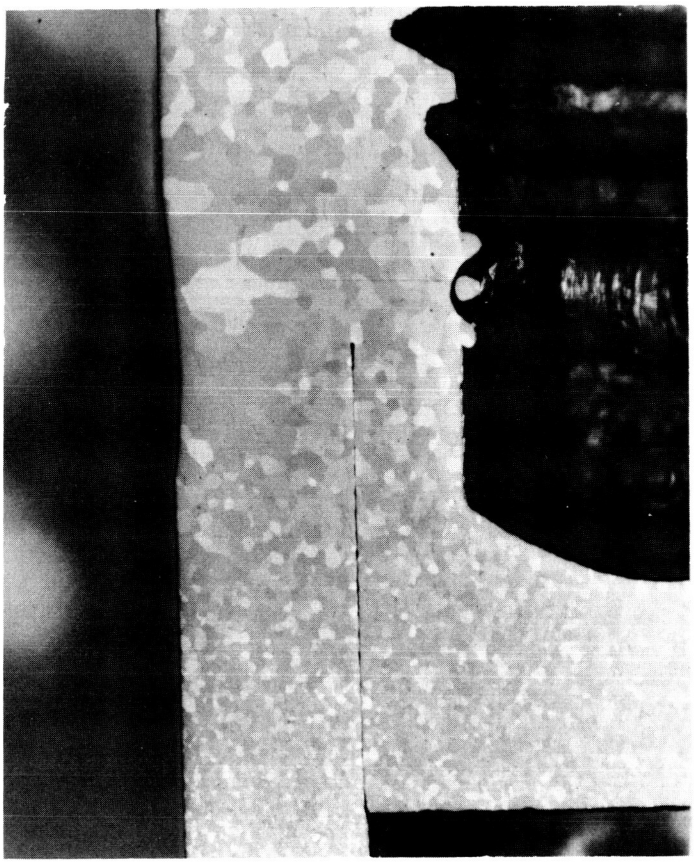
DM-1

DM-3

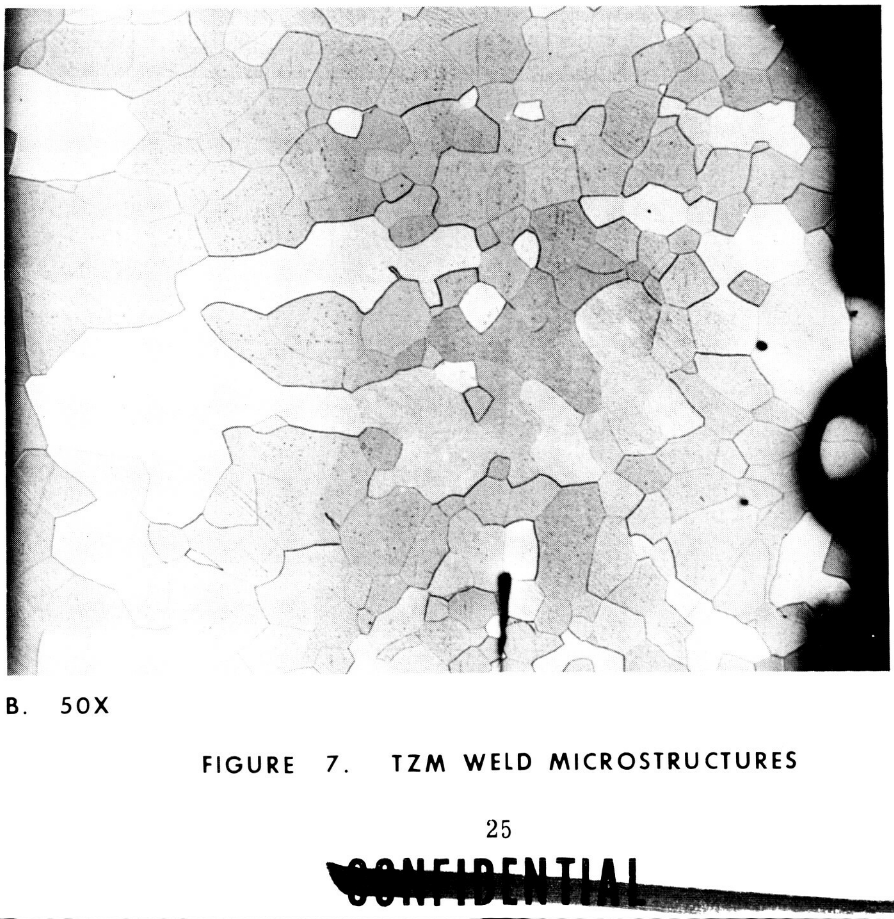
DM-4

DM-5

FIGURE 6. TZM PROTOTYPE FUEL PINS



A. 16X



B. 50X

FIGURE 7. TZM WELD MICROSTRUCTURES

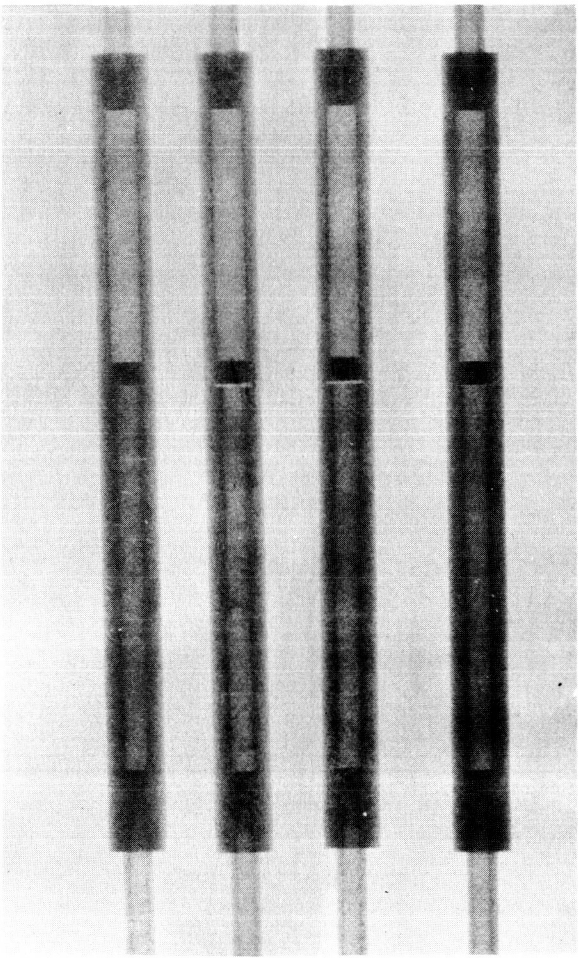
to a depth equal to the wall thickness of the cladding. Porosity in the weld area is at a minimum, and grain growth is not excessive.

After the fuel pins were removed from the welding chamber, they were examined and inspected. All dimensions were measured. Straightness and concentricity of the welded components were determined. The welded pin was leak checked with a helium leak detector capable of detecting leak rates of 10^{-10} cc/sec. The leak detection technique involved placing the sample in a vacuum chamber, evacuating the chamber, and then introducing helium into the chamber. If the sample contained a leak, helium then would enter the pin and would be detected subsequently when the sample was again evacuated in the leak detector system.

X-ray and neutron radiographic techniques were employed as non-destructive techniques to determine weld integrity and penetration, component integrity, and component location in the assembled and welded fuel pin. Neutron radiography, as exhibited in Figure 8, offers a unique technique to define fuel movement and to show fuel detail during and after irradiation. It is shown here to reference the pre-irradiation condition of the fuel in the pins. X-ray radiography, as depicted in Figure 9, offered better resolution of the weld zone, and was used mainly for that reason.

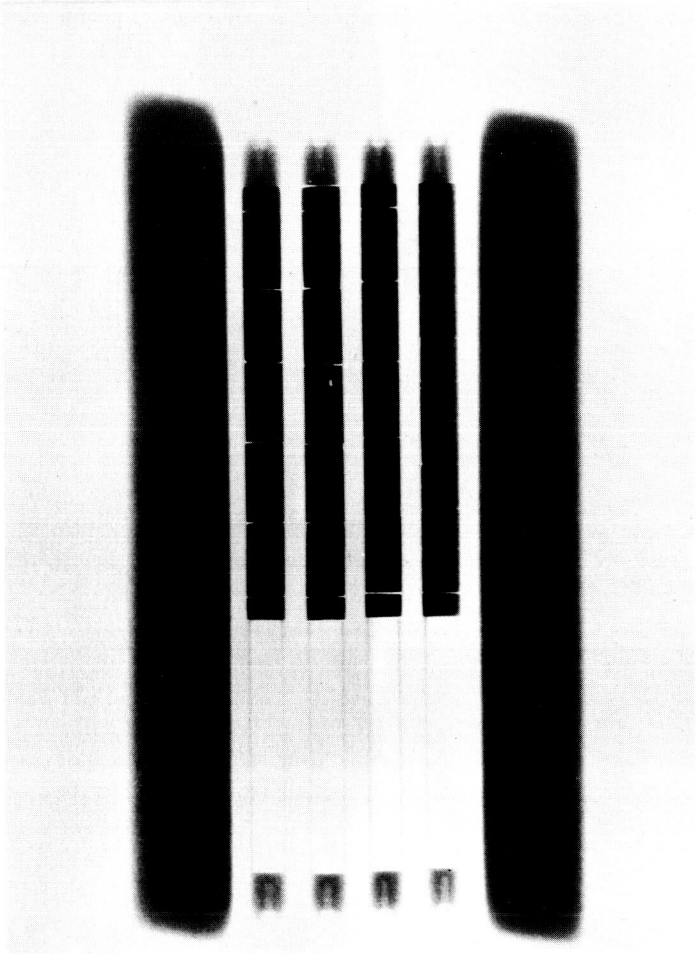
B. Prototype Fuel Pin Production

To demonstrate the fabrication, characterization, and inspection techniques described above, four prototype fuel pins containing depleted UO_2 clad in TZM were produced and examined. These prototypes are described in detail in APED 5042-A,



DM-5 DM-4 DM-3 DM-1

FIGURE 8. NEUTRON RADIOGRAPHS OF TZM PROTOTYPE FUEL PINS. DARKER AREAS INDICATE HIGHER NEUTRON ATTENUATION



DM-5 DM-3

DM-4 DM-1

FIGURE 9. X-RAY RADIOGRAPHS OF TZM PROTOTYPE FUEL PINS. DARKER AREAS INDICATE GREATER MASS

"Report No. 3A, Fabrication Process Evaluation-TZM Cladding."

C. Enriched Fuel Pin Production

After the TZM prototypes had been examined and approved, six fuel pins containing 93.15% enriched UO_2 were produced for irradiation testing. A characterization of the UO_2 used for fuel and insulators is shown in Table 3. The TZM is described in Appendix A, Table 1A. Fabrication techniques employed are those described previously.

The enriched fuel pins, shown in Figure 10, were inspected after fabrication. Dimensional measurements for all components and assemblies are given in Table 4. All dimensions are within the final design tolerances. Densities of all fuel pin components were measured by the bulk immersion technique and are presented in Table 5. All materials employed met density specifications, as shown. Actual UO_2 fuel and insulator weights included in the fuel pin are listed in Table 6.

The fuel pins were leak checked and radiographed after fabrication. No leaks were found. Radiographs, as shown in Figure 11, indicated that sound, full-penetration welds were achieved in all fuel pins. The radiographs also verified that components had been assembled in the correct order.

VI. W-25 Re FUEL PIN FABRICATION

The W-25 Re cladding, plenum tubing, and thermocouple tubing components were fabricated by San Fernando Laboratories. Bar stock for the W-25 Re end plugs was supplied by Rembar Company, Inc. Details of the fabrication of these components are described in Appendix B.

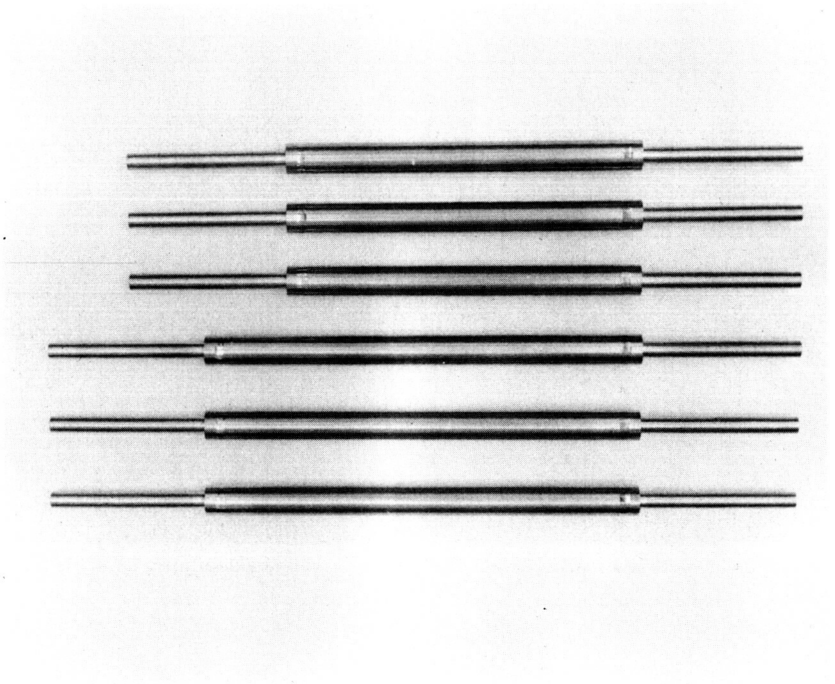


FIGURE 10. ENRICHED FUEL PINS

TABLE 4. Dimensions of Enriched Fuel Pin Components and Assembly

Dimension (in.)	Specification	EM-1	EM-2	EM-3	EM-4	EM-5	EM-6
UO_2 Fuel Pellet o.d.	0.197±0.001	0.196-0.198	0.196-0.198	0.196-0.198	0.196-0.198	0.196-0.198	0.196-0.198
UO_2 Fuel Pellet i.d.	0.120±0.001	0.119-0.120	0.119-0.120	0.119-0.120	0.119-0.120	0.119-0.120	0.119-0.120
Fuel Column Length	2.00 ±0.01	1.995	1.994	1.999	2.004	2.008	1.993
Number of Individual Fuel Pellets	8-12	9	9	9	9	9	9
UO_2 Insulator dia.	0.197±0.001	0.196-0.197	0.196-0.197	0.196-0.197	0.196-0.197	0.196-0.197	0.196-0.197
UO_2 Insulator Length	0.125±0.002	0.125-0.127	0.126-0.127	0.124-0.127	0.126-0.127	0.126-0.127	0.126-0.127
TZM Clad Wall Thickness	0.050±0.001	.0495-.0505	.0495-.0505	.0495-.0505	.0495-.0505	.0495-.0505	.0495-.0505
TZM Clad o.d.	0.302±0.003	0.301-0.302	0.301-0.302	0.301-0.302	0.301-0.302	0.301-0.302	0.301-0.302
TZM Clad i.d.	0.202±0.001	0.201-0.202	0.201-0.202	0.201-0.202	0.201-0.202	0.201-0.202	0.201-0.202
TZM Clad Length (1-3)	3.05 ±0.01	3.050	3.049	3.051			
TZM Clad Length (4-6)	3.85 ±0.01				3.851	3.850	3.859
TZM Plenum Sleeve o.d.	0.198±0.001	0.198-0.199	0.198-0.199	0.198-0.199	0.198-0.199	0.198-0.199	0.198-0.199
TZM Plenum Sleeve i.d.	0.158±0.001	0.158-0.159	0.158-0.159	0.158-0.159	0.158-0.159	0.158-0.159	0.158-0.159
TZM Plenum Sleeve Length (1-3)	0.44 ±0.01	0.439	0.438	0.436			
TZM Plenum Sleeve Length (4-6)	1.24 ±0.01				1.238	1.238	1.239
Fuel Support Sleeve Thickness	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Axial Void Length	0.060±0.010	0.065	0.067	0.062	0.060	0.050	0.064
Total Pin Length (A) (1-3)	6.35 ±0.01	6.341	6.347	6.348			
Total Pin Length (4-6)	7.15 ±0.01				7.151	7.144	7.146
Concentricity-Middle to End T.I.R.		<0.007	<0.007	<0.007	<0.007	<0.007	<0.007

TABLE 5. Densities of Enriched Fuel Pin Components

Component	Specification	EM-1	EM-2	EM-3	EM-4	EM-5	EM-6
Enriched UO_2 Fuel Column (g/cm^3)	10.42±0.104	10.39	10.42	10.50	10.51	10.42	10.35
Enriched UO_2 Fuel Column (% T.D.)	95±1	94.71	94.9	95.72	95.80	94.99	94.35
Depleted UO_2 Insulator (g/cm^3)	10.42±0.104	10.42-10.53	10.42-10.53	10.42-10.53	10.42-10.53	10.42-10.53	10.42-10.53
Depleted UO_2 Insulator (% T.D.)	95±1	95.0 -96.0	95.0 -96.0	95.0 -96.0	95.0 -96.0	95.0 -96.0	95.0 -96.0
TZM Clad (g/cm^3)	> 10.1	10.15-10.20	10.15-10.20	10.15-10.20	10.15010.20	10.15-10.20	10.15-10.20
TZM Plenum Sleeve (g/cm^3)	> 10.1	10.10-10.20	10.10-10.20	10.10-10.20	10.10-10.20	10.10-10.20	10.10-10.20
TZM End Plug (g/cm^3)	> 10.1	10.10-10.20	10.10-10.20	10.10-10.20	10.10-10.20	10.10-10.20	10.10-10.20
Tungsten Fuel Support Sleeve (g/cm^3)	> 19.1	19.1 -19.2	19.1 -19.2	19.1 -19.2	19.1 -19.2	19.1 -19.2	19.1 -19.2

TABLE 6. Uranium Weights in Enriched Fuel Pins

	EM-1	EM-2	EM-3	EM-4	EM-5	EM-6
Total Weight of 93.15% Enriched UO_2 Fuel Column (grams)	6.36	6.34	6.38	6.38	6.41	6.35
U-235 Weight of Fuel Column (grams)	5.22	5.20	5.23	5.22	5.25	5.21
Total Weight of Depleted UO_2 Insulators (grams)	1.30	1.32	1.24	1.31	1.31	1.27
U-235 Weight of Insulators (grams)	0.0029	0.0029	0.0027	0.0029	0.0029	0.0028

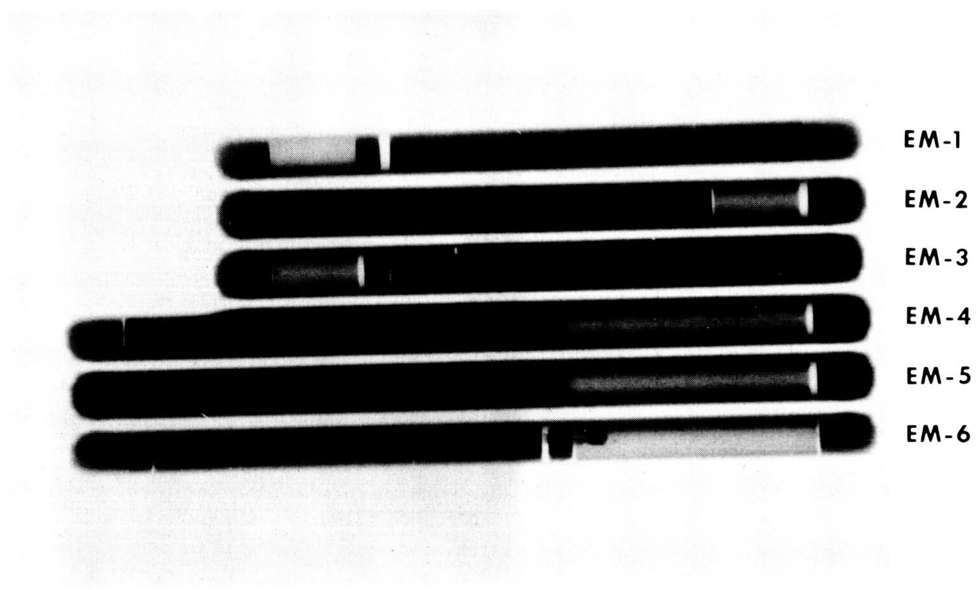


FIGURE 11. X-RAY RADIOGRAPHS OF TZM ENRICHED FUEL PINS. DARKER AREAS INDICATE GREATER MASS

The W-25 Re end plug was a two-piece brazed assembly. The end plug weld closure was machined from rod stock. The extreme hardness of this lot of W-25 Re alloy made machining operations difficult, time-consuming, and expensive. The outer surfaces of the end plug were turned conventionally on a lathe. Tungsten carbide tools and slow turning speeds were employed. The holes in the end plug used for holding the thermocouple guard tube could not be made with carbide drills. Electrical discharge machining (EDM) techniques were therefore used to form these holes. The thermocouple tubing portion of the end plug, together with the cladding and plenum tubing, required only an operation to cut to length. The procedure employed for cutting was the same as that described for TZM.

All W-25 Re components were cleaned prior to brazing, welding, and loading operations. The cleaning procedure involved the following steps:

- Immersion in Oakite degreasing solution and alkaline cleaner.
- Rinse in hot water.
- Immersion in hydrochloric acid solution.
- Two rinses in deionized water.
- Two rinses in methanol.
- Firing at $1000^{\circ}C$ for 15 minutes in wet hydrogen atmosphere.

Wet hydrogen was used in the firing operation to assure the removal of any carbon-containing impurities remaining after the chemical cleaning treatment.

The 0.001 in. tungsten fuel sleeve was subjected to the first five cleaning steps, but was not fired because of the possibility of recrystallization.

A Mo-50 Re brazing alloy was used to join the thermocouple tube to the end plug. The tube was inserted into the hole of the end plug. A piece of Mo-50 Re wire (0.020 in. diam.) was wrapped around the tube just above the joint interface. The assembly was then held at 2550°C for 2 minutes in vacuum to make the braze. The recrystallized microstructure of the brazed joint is shown in Figure 12. As can be noted, a sound, single-phase structure with a minimum of porosity was achieved in the brazed joint.

The brazed end plug was joined to the W-25 Re cladding by electron beam welding. The same positioning, preheating, and welding techniques described previously for the TZM components were employed for W-25 Re. A typical weld microstructure is shown in Figure 13. The polished section was etched electrolytically in a solution containing 5% sodium hydroxide. As can be noted, the weld penetrated to the full thickness of the cladding wall. A minimum of porosity and distortion was found in the weld zone. All welds were helium leak tested and found to be leak-tight. The completed assembly, after brazing and welding, is shown in Figure 14.

Techniques of assembly and loading of the W-25 Re fuel pins were to be identical to those employed for TZM fuel pin fabrication. The same dimentional, leak testing, and x-ray and neutron radiographic inspection techniques also can be applied to the W-25 Re fuel pins.

50X Etched

Braze

FIGURE 12. MICROSTRUCTURE OF W-25 Re BRAZED WITH Mo-50 Re BRAZING ALLOY

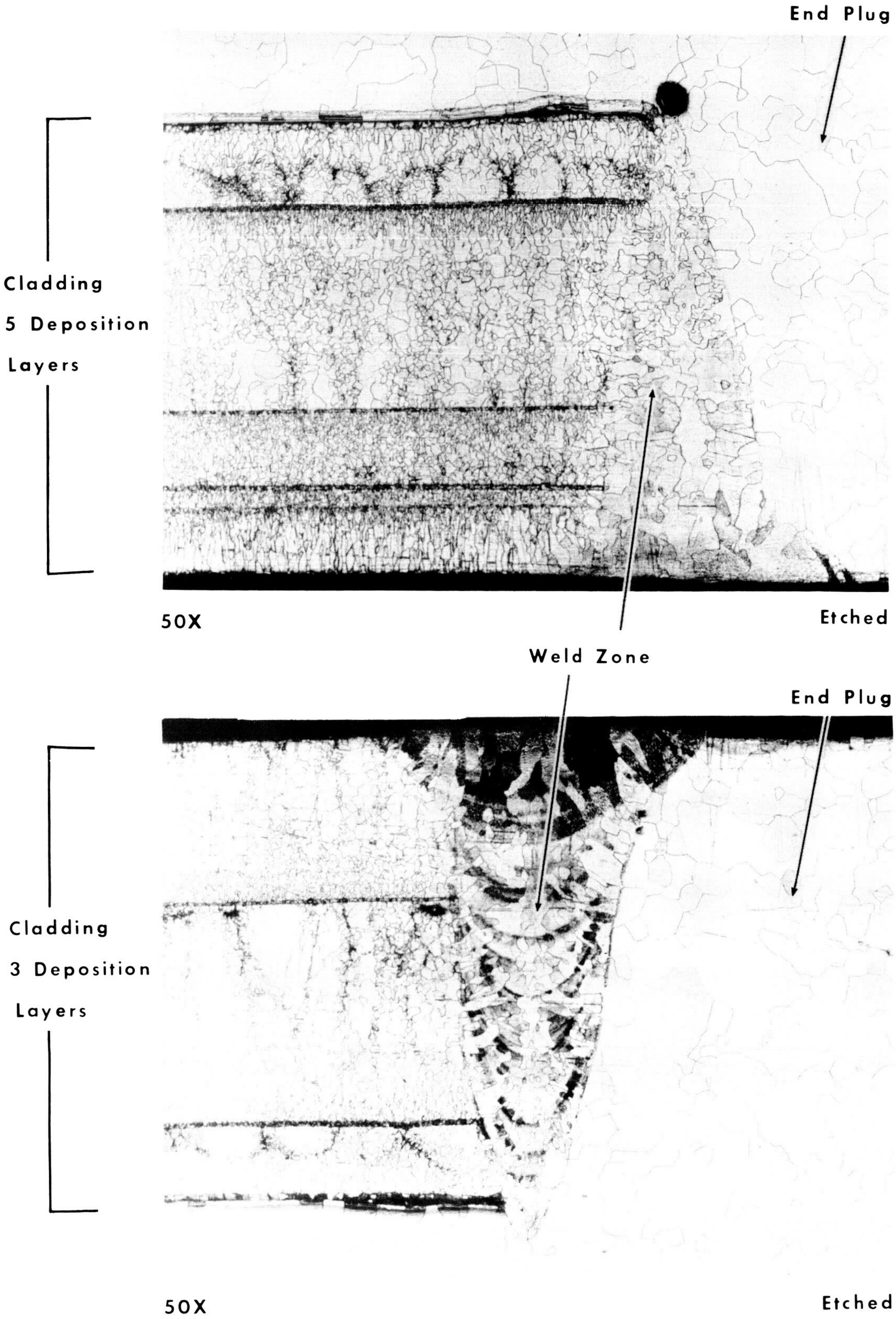


FIGURE 13. W-25 Re WELD MICROSTRUCTURES

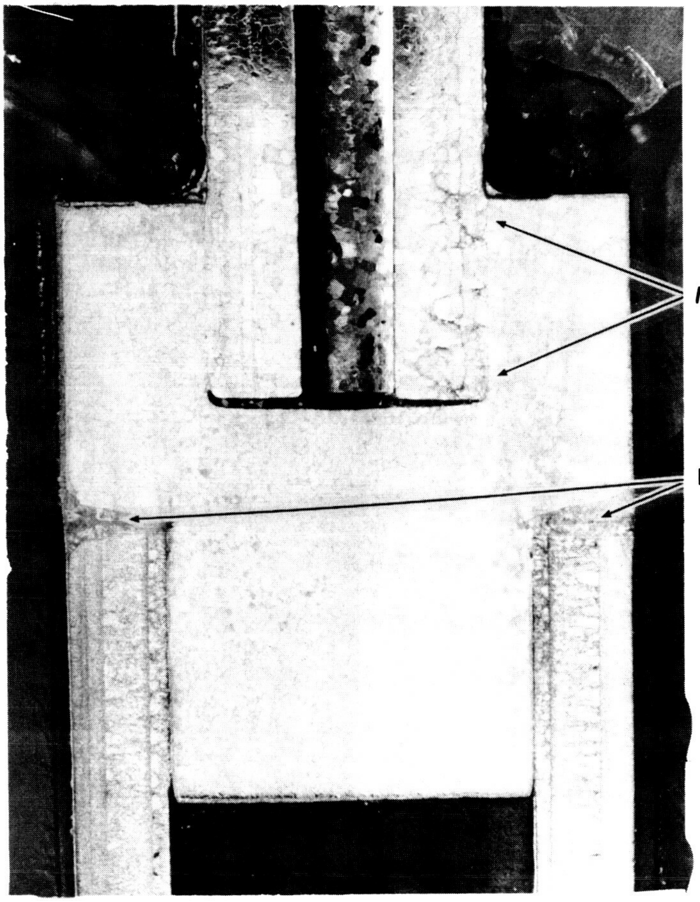


FIGURE 14. W-25 Re END PLUG CLOSURES

VII. CONCLUSIONS

1. Designs were developed to utilize TZM, W-25 Re, and W-30 Re-30 Mo cladding with bulk or cermet UO_2 fuel in fuel pins capable of being operated at a maximum heat flux of 2 kW/in^2, maximum clad surface temperature of 2500°F, and maximum burnup of 5×10^{20} fuel atoms per cubic centimeter of pin.

2. The TZM and W-25 Re cladding-bulk UO_2 fuel combinations were selected for fabrication of fuel pins.

3. Techniques were developed to produce annular UO_2 fuel pellets with a wall thickness of 0.030 in. and an o.d. of 0.200 inches. The cold pressing and sintering technique was found to result in about 10% loss of pellets by breakage. All of the breakage occurred during pressing and handling; therefore, the broken pellets could be reprocessed with a minimum of effort.

4. Prototype pins were produced using TZM cladding and depleted UO_2 annular fuel with a wall thickness of 0.040 inches. With this wall thickness, the breakage rate was less than 1%. The purpose of the prototype production was to demonstrate fabrication techniques and inspection procedures.

5. TZM-clad fuel pins containing enriched UO_2, suitable for irradiation testing at the desired reactor operating conditions, were produced and tested by the procedures established in prototype production.

6. Techniques were developed to fabricate the prototype and irradiation pins with W-25 Re cladding. The purchased cladding material did not meet specified compositional tolerances; therefore, no pins were fabricated.

7. The processes used for fabrication of TZM tubing and UO_2 thin-wall fuel were representative of processes that can be scaled up to produce large volumes of fuel rods having lengths over three feet. The same comment is applicable to thick-wall (0.20 in o.d. x 0.04 in. i.d.) UO_2 fuel used in Type I fuel designs. The main question in scale-up could be the ability of the vendors to meet the same dimensional tolerances on longer lengths of TZM tubing that were used for the small fuel pins.

8. The vapor co-deposition process used for fabrication of the W-25 Re tubing was found to be unsuitable for scale-up at this time. The W-25 Re vapor-deposition product was found to have problems in both quality and production. The production problem was related to variability in the impurity content of the ReF_6 and insufficient knowledge of process conditions and control for the cladding dimensions required as detailed in Appendix B. The quality problem was closely related to the production difficulties, which were not originally anticipated, and specifically to the failure in meeting specifications set for the material. These problems could be eliminated if a vendor was developed to produce the desired alloy by the use of traditional methods.

APPENDIX A

Fabrication of TZM Tubing at Climax Molybdenum Company

All of the TZM tubing was produced by Climax by the extrusion, rolling, swaging, and gun drilling of an arc-melted ingot. Hydrogen-reduced molybdenum powder and the small amounts of TZM additions were formed into about an 11-inch carbon-deoxidized, vacuum arc-melted ingot. The ingot was then forward extruded to about a 6-inch diameter. It was rolled to near a 2-inch diameter and then swaged to a rod about 3/8-inch diameter. At this point, the rod was stress relieved by holding for 1/2 hour at 2200°F. The required o.d. of the tubing was established by centerless grinding. Finally, the tube was drilled and honed by gun drilling techniques.

A characterization of the specific lot of material used for fuel pin fabrication is shown in Table 1A. The structure of the tubing is fibrous in the longitudinal direction with a fragmented, coherent grain structure. The titanium carbide and zirconium carbide present occur as very small precipitates within the grains, as can be seen in Figure 7-B. Mechanical properties of the lot of TZM supplied by Climax for the fuel pin components were measured. The ultimate and 0.2% yield strengths were 118.9-123.4 ksi and 103.3-114.3 ksi, respectively. The elongation on a gage length of four times the diameter was 30-38%, and the hardness was found to be 227-292 DPN.

Climax had indicated by personal communication that the gun drilling technique has produced TZM of better quality than can be obtained by conventional tubing extrusion processes and is being adapted for large-scale production. Climax has stated that cladding lengths up to 5 feet could be produced with the same tolerances as were obtained on the 5-inch pieces supplied for the fabrication of fuel pins in this program. However, the 4.2-inch samples made for this program represent the longest length which actually has been fabricated by Climax to these dimensions and tolerances. Fabrication costs can be expected to increase exponentially as lengths are increased over 4 inches.

TABLE 1A. Characterization of TZM Components

	TZM Cladding	TZM Plenum Sleeve	TZM End Plug
Ti	5100 ppm	5000 ppm	5300 ppm
Zr	800	1000	1000
C	250	160	210
Mo	Balance	Balance	Balance
Ca	< 10		
Cr	< 10		
Co	< 10		
Cu	< 10		
Fe	10	30	< 10
Pb	< 10		
Mg	< 10		
Ni	< 10	< 10	< 10
Si	20	< 10	< 10
O_2	6	2	< 4
H_2	< 1	< 1	< 1
N_2	5	< 1	< 2

APPENDIX B

Fabrication of W-25 Re Tubing at San Fernando Laboratories

A vapor deposition process was used by San Fernando Laboratories to produce the W-25 Re components used for the cladding, plenum sleeve, and thermocouple tubing in the fuel pin design. The tubing shapes were chemically vapor co-deposited from WF_6 and ReF_6 in a hydrogen atmosphere at 650-700°C. Composition was controlled by maintaining the WF_6-ReF_6 ratio at three.

The tubing was constructed by depositing one to four laminated layers to a diameter approximately 0.020-0.030 inch larger than required. The laminated deposits were centerless ground, acid pickled, and hydrogen cleaned at 850°C before deposition of the successive layer. After deposition, the tubing was heat-treated at 2000°C for one hour to recrystallize to eliminate sigma phase, and to stress relieve the material. The tubes were ground between centers to the specified dimensions, dye checked for cracks or imperfections, and then analyzed for rhenium content.

The typical impurity specification maintained in the W-25 Re vapor co-deposited alloy is presented in Table I-B. Experience gained by San Fernando Laboratories has indicated that these impurities should pose no problems for applications to 2500°C. In the past, a problem has been caused when fluorine content was above 50 ppm. Tubing containing this amount of residual fluorine has exhibited considerable metal swelling after being held at 2500°C for one hour. However, San Fernando has solved this problem by a proprietary procedure which effects a preferential removal of excess fluoride ions from the gases as they react with the hydrogen at the mandrel. The procedure does not increase the impurity level of any other interstitial constituent, and does permit the control of fluorine at levels between 5 and 50 ppm.

Three major problems were experienced by San Fernando in production of the W-25 Re tubing for use in the fuel pin fabrication. These problems

TABLE 1B. Typical Impurity Specification of San Fernando Laboratory's Vapor Co-deposited W-25 Re Tubing

Element	Content (ppm)
Al	2
Cr	17
Cu	0.5
Fe	20
Mg	1
Mn	0.5
Ni	2
Si	10
C	13
N	3
O	4
H	2
F	< 50

are considered below:

1. Maintenance of concentricity between the o. d. and i. d. of the tubing.

2. Maintenance of uniform rhenium contents of 25 ± 0.5% from lot to lot and along the length of each tube.

3. Procurement of ReF_6.

These problems resulted in considerable delays in the fabrication schedule of the tubing. In addition, the first two problems directly affected the quality of tubing produced.

The problem with concentricity was attributed by San Fernando to unanticipated difficulty in handling the particular size-composition combination. Although only the thermocouple tubing was found to be grossly out of specification after delivery, the concentricity of the cladding varied sufficiently over even an 8-inch length at the time of manufacture to make it desirable for San Fernando to cut the pieces to 4-inch lengths for grinding to uniform wall size. While wall thickness obtained by this technique is uniform, one side of the wall may contain three deposition layers while the other side may contain up to five layers. Possible causes for the problems are: channeling of the volatile fluoride gas which tended to increase concentration of the gas (and consequently build-up rate) on one side of the mandrel, or sagging of the mandrel during deposition of this particular tubing which had a large wall thickness relative to the inner diameter.

Maintenance of uniform rhenium content of 25 ± 0.5% from lot to lot and along the length was not attained by the manufacturer. Table 2-B shows the extent of the non-uniformity of Re content in the various tubings fabricated for the fuel pins. The principal variation at the ends of the mandrel (cropped off and discarded) is due to the fact that ReF_6 decomposes at a lower temperature than does WF_6; this causes an enrichment of Re at the cool ends of the mandrel. The lower stability of ReF_6 causes the more rapid depletion of

TABLE 2B. Variation in Rhenium Content of W-25 Re Fuel Pin Components Fabricated by San Fernando Laboratories

Component	Lot	Rhenium Content (wt %)
Cladding	1	26, 26
	1A	26
	2A	27, 21
	3A	25, 24
	4A	22
Plenum Sleeve	1	22
Thermocouple End Tube	1	26, 24

TABLE 3B. Typical Variation in Rhenium Content Along 5-Foot Length of W-25 Re Vapor Co-deposited Tubing

Distance from End of Tube - (ft)	Tube 1 (%Re)	Tube 2 (%Re)
0	26.7	25.6
1	25.9	24.9
2	24.2	23.8
3	23.9	24.3
4	24.8	25.4
5	26.1	26.9

ReF_6 than of WF_6 from the gas stream and causes the Re content of the deposit to be lower at the middle of the rod. The normal variation in Re content along a five-foot length of tubing is shown in Table 3-B. San Fernando does take steps to minimize this variation by a proprietary method of gas injection. The extreme variations in Re content shown in Table 2-B are attributed to slight localized mandrel temperature excursions of short time duration during deposition. Generally, heat-treated W-Re tubing compositional uniformity varies less than 0.5% in any radial section. The problem of non-uniformity along the length can usually be circumvented by using only the center section of the deposited material. Accordingly, at San Fernando's request, the 12-inch lengths originally requested for the fuel pin fabrication were reduced to 4 inches. However, as is evidenced in Table 2-B, the problem was not solved satisfactorily.

San Fernando has attributed the fabrication schedule delays and a share of the quality control problems primarily to ReF_6 procurement difficulties. The ReF_6 is made to order and requires about 4-6 weeks lead time. In late Fall, 1966, the ReF_6 shipping containers were changed from pure nickel to low alloy steel. San Fernando was not appraised of the situation until May 1967. During the same period, San Fernando was without usable ReF_6 from January 1 through March 1 and between March 20 and April 15. Then they were supplied with a quantity sufficient to produce only a part of the required fuel pin components.

[redacted]

APPENDIX C

Fabrication Drawings for Type I and Type II Fuel Pins

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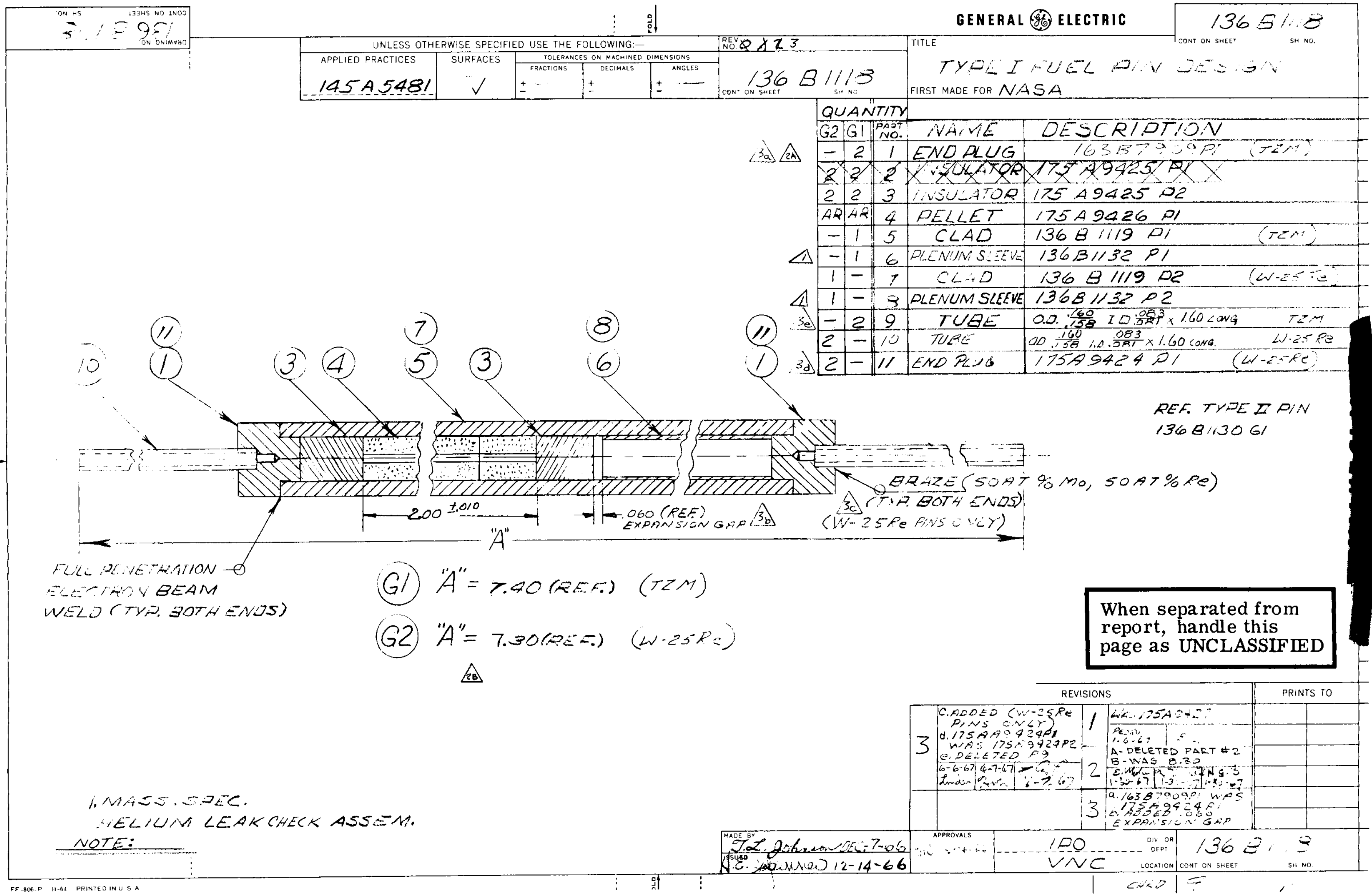

QUANTITY G2	G1	PART NO.	NAME	DESCRIPTION	
—	2	1	END PLUG	163B7909P1	(TZM)
~~2~~	~~2~~	~~2~~	~~INSULATOR~~	~~175A9425 P1~~	
2	2	3	INSULATOR	175 A9425 P2	
AR	AR	4	PELLET	175 A9426 P1	
—	1	5	CLAD	136 B 1119 P1	(TZM)
—	1	6	PLENUM SLEEVE	136B1132 P1	
1	—	7	CLAD	136 B 1119 P2	(W-25Re)
1	—	8	PLENUM SLEEVE	136B1132 P2	
—	2	9	TUBE	O.D. .160/.158 I.D. .083/.081 x 1.60 LONG	TZM
2	—	10	TUBE	O.D. .160/.158 I.D. .083/.081 x 1.60 LONG	W-25Re
2	—	11	END PLUG	175A9424 P1	(W-25Re)

FIGURE C1. TYPE I FUEL PIN DESIGN

[redacted]

[redacted]

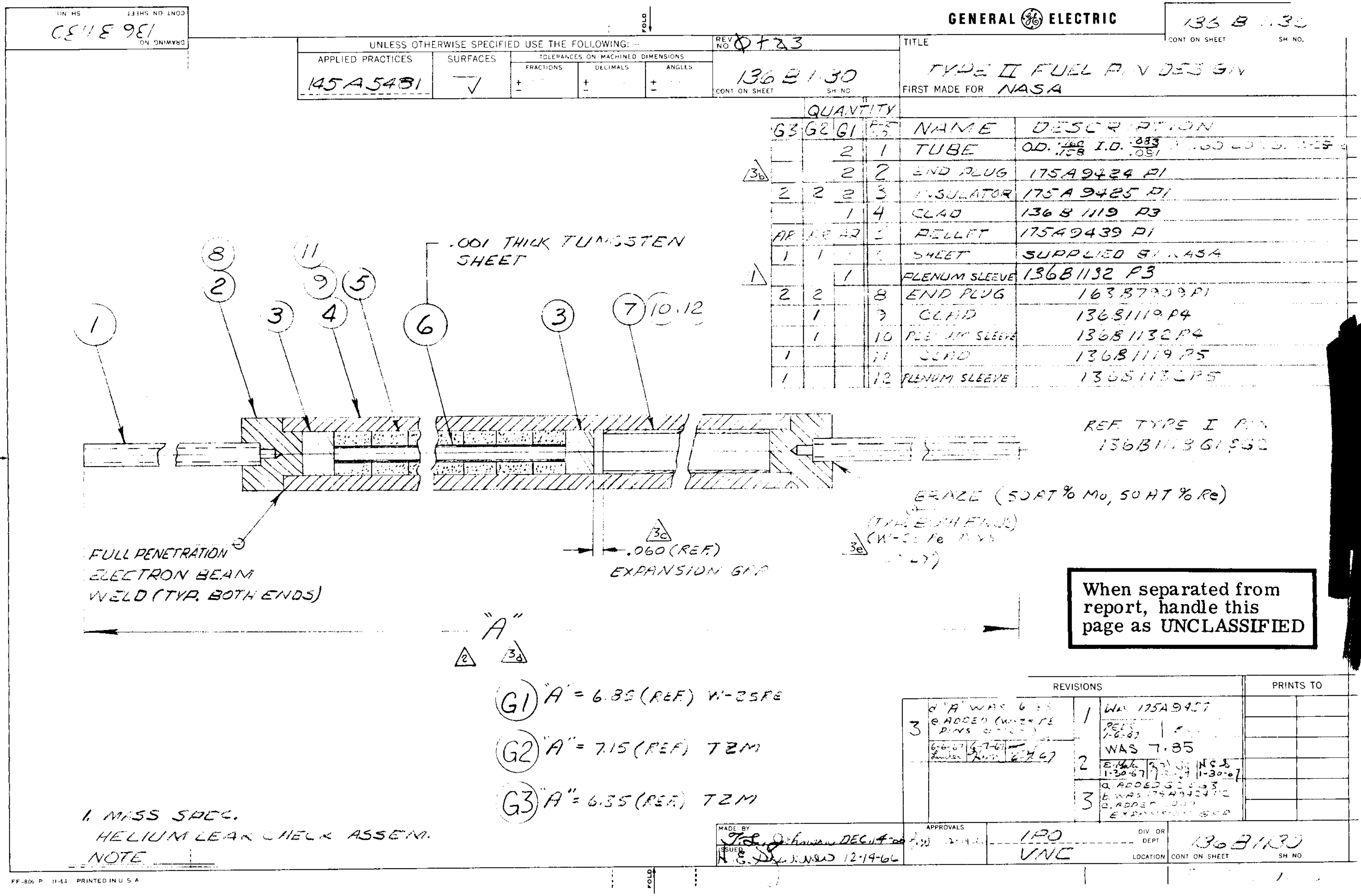

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FIGURE C2. TYPE II FUEL PIN DESIGN

[redacted]

[redacted]

GENERAL ELECTRIC

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136B119	5/1

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APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS FRACTIONS	DECIMALS	ANGLES
145A5481	63/	± —	± —	± —

REV NO ~~0~~ 1 2

136B1119 CONT ON SHEET SH NO.

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NEXT ASSEMBLY 136B1130 G1

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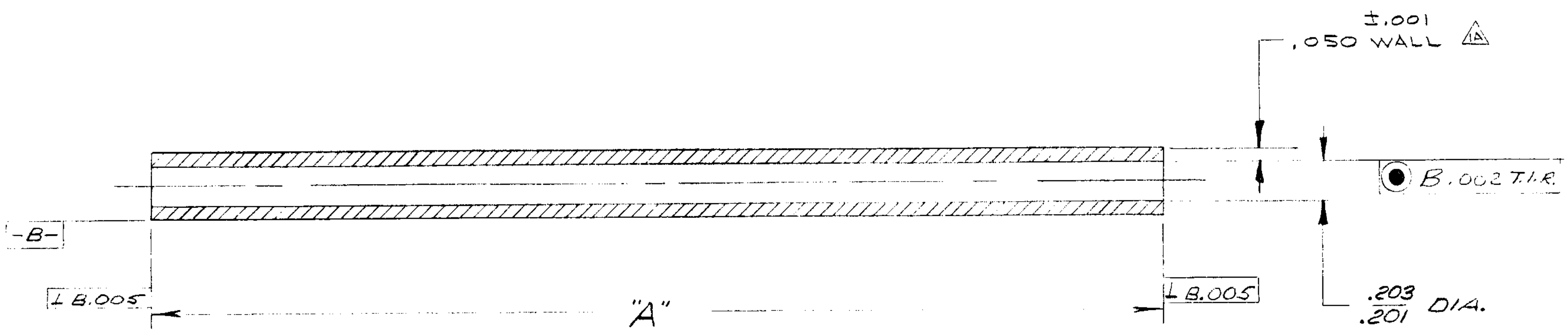

PART NO.	MAT'L.	PIN	"A" DIM. ±.010	
1	TZM	TYPE I	4.10	
2	W-25Re	TYPE I	4.00	1B
3	W-25Re	TYPE II	3.55	1C
4	TZM	TYPE II	3.85	
5	TZM	TYPE II	3.05	

2. All W-25 Re to be to the following physical and chemical specifications;
   Density greater than 99.0% of theoretical.
   Leak rate less than 1 x 10^{-10} cc/sec on He M.S.
   Re content of 24 ± 1.5%
   No sigma phase particles larger than 15 microns in any dimension, no more than 5 particles larger than 5 microns in an area of 1 in. diam.
   In ppm; C<30, N<15, O<40, H<15, F<20, Al<15, Ta<300, Cr<15, Cd<100, Cu<15, Fe<70, Hf<75, Mo<200, Ni<15, Ti<15.

1. All TZM to the following physical and chemical specifications:
   Density greater than 99.9% of theoretical.
   Leak rate less than 1 x 10^{-10} cc/sec on He M.S.
   Elemental content (in wt %) Mo>99.0, Ti 0.4 - 0.55, Zr .06-.12, C .01-04, Fe<.015, H<.0015, K<.0015, N<.003, Ni<.003, O<.005, Si<.030, Sn<.006, W<.008, Al<.005, Ca<.004, Co<.004, Cr<.006, Cu<.004, Pb<.004, Mg<.004, Mn<.004, Na<.002.

NOTES:

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1	A-WAS .300/.302 O.D. B-"A" WAS 5.00 C-"A" WAS 4.55	
2	ADDED P4 & P5 AND CONCENTRICITY	

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FIGURE C3. CLAD

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DRAWING NO. 136 B 1132

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APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS: FRACTIONS	DECIMALS	ANGLES
145 A 5481	√	±	±	±

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TITLE: PLENUM SLEEVE

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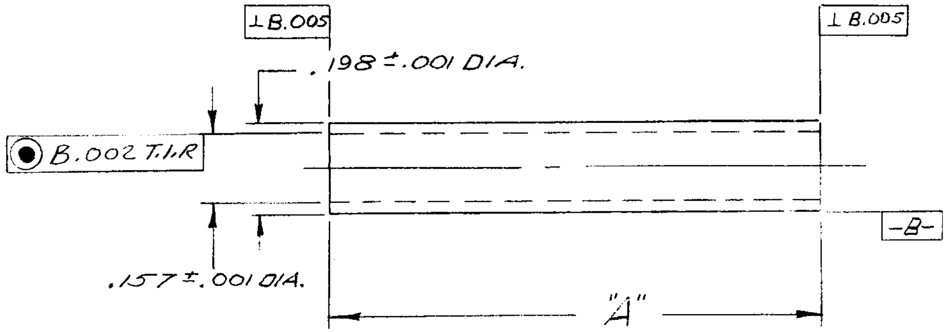
NEXT ASSEMBLY 136 B 1130 G1



PART NO.	MATL.	PIN	"A" DIM. ±.010
1	TZM	TYPE I	1.24
2	W-25 Re	TYPE I	1.14
3	W-25 Re	TYPE II	0.94
4	TZM	TYPE II	1.24
5	TZM	TYPE II	0.94

2. All W-25 Re to be to the following physical and chemical specifications:
   Density greater than 99.0% of theoretical.
   Leak rate less than 1 x 10^{-10} cc/sec on He M.S.
   Re content of 24 ± 1.5%
   No sigma phase particles larger than 15 microns in any dimension, no more than 5 particles larger than 5 microns in an area of 1 in. diam.
   In ppm: C <30, N <15, O <40, H <15, F <20, Al <15, Ta <300, Cr <15, Cd <100, Cu <15, Fe <70, Hf <75, Mo <200, Ni <15, Ti <15.

1. All TZM to the following physical and chemical specifications:
   Density greater than 99.9% of theoretical.
   Leak rate less than 1 x 10^{-10} cc/sec. on He M.S.
   Elemental content (in wt %) Mo > 99.0, Ti 0.4 – 0.55, Zr .06–.12, C .01–04, Fe <.015, H <.0015, K <.0015, N <.003, Ni <.003, O <.005, Si <.030, Sn <.006, W <.008, Al <.005, Ca <.004, Co <.004, Cr <.006, Cu <.004, Pb <.004, Mg <.004, Mn <.004, Na <.002.

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1	A-WAS 2.20 LG. B-WAS 2.00 LG. E.M. 1-30-67 / 1-30-67 / 1-30-67	
2	a. ADDED PAGES. b. 1.29 WAS 1.30 c. 1.14 WAS 1.20 d. 0.94 WAS 1.00 e. ADDED CONCENTRICITY 6-6-67 6-7-67 6-7-67	

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FIGURE C4. PLENUM SLEEVE

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175 A 9425

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TITLE

INSULATOR

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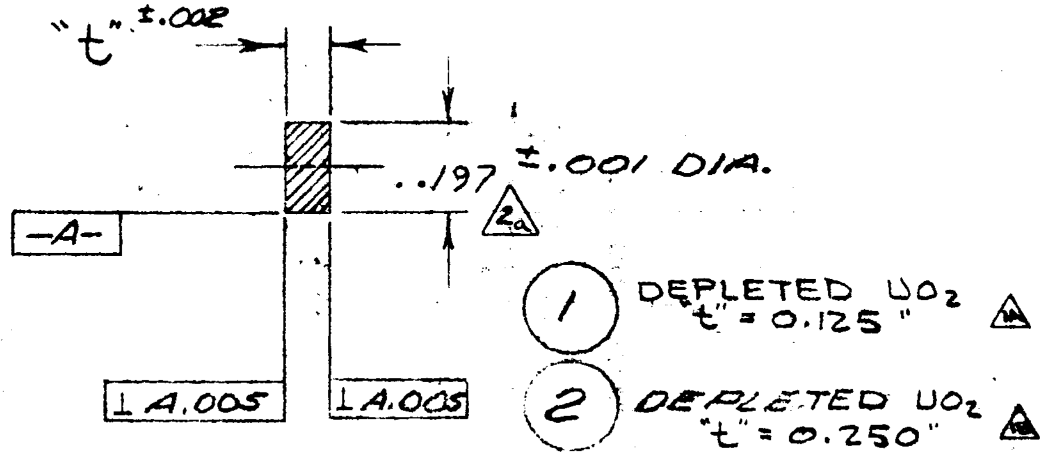

All UO_2 will have a bulk density of 95 ± 1% of theoretical density and a ratio of oxygen-uranium atoms of 2.005 ± .005. The UO_2 chemical specification is shown below:

Total Impurity Content < 2500 ppm

Ca < 400 ppm	Mo < 25 ppm
C < 100 ppm	Sn < 15 ppm
Mg < 400 ppm	Cu < 10 ppm
Si < 200 ppm	Pb < 5 ppm
Fe < 200 ppm	Ag < 1 ppm
Al < 150 ppm	Cd < 0.5 ppm
Ni < 60 ppm	B < 0.25 ppm
Cr < 35 ppm	

1.

Total Halides < 25 ppm

NOTE:

UNLESS OTHERWISE SPECIFIED USE	APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS		
			FRACTIONS	DECIMALS	ANGLES
	145A5481	√	±	±	±

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1	A-WAS W-25RE B-WAS .125 THK. 1-30-67 1-30-67 1-30-67	
2	a. .197 WAS .200 b CHANGED NOTE 1. 5-6-67 5-7-67 5-8-67	

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FIGURE C5. INSULATOR

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GENERAL ELECTRIC

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:				
APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS: FRACTIONS	DECIMALS	ANGLES
145A5481	125√	± —	±.005	± —

REV NO 0 — 163B7909 — CONT ON SHEET — SH NO

TITLE: END PLUG

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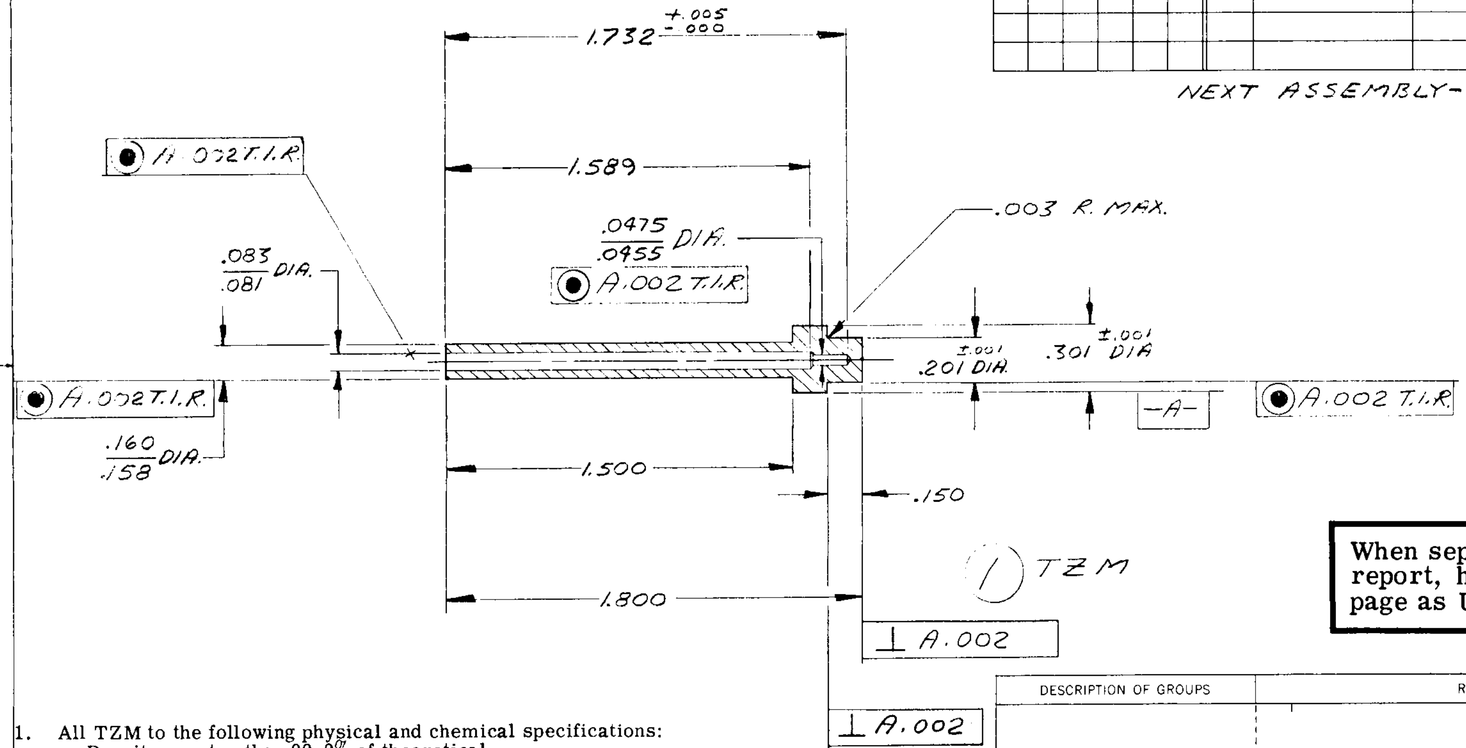

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DESCRIPTION OF GROUPS	REVISIONS	PRINTS TO

1. All TZM to the following physical and chemical specifications:
   Density greater than 99.9% of theoretical.
   Leak rate less than 1 x 10^{-10} cc/sec on He M.S.
   Elemental content (in wt %) Mo > 99.0, Ti 0.4 - 0.55, Zr .06-.12, C .01-04,
   Fe < .015, H < .0015, K < .0015, N < .003, Ni < .003, O < .005, Si < .030, Sn < .006,
   W < .008, Al < .005, Ca < .004, Co < .004, Cr < .006, Cu < .004, Pb < .004 Mg < .004
   Mn < .004, Na < .002.

NOTES:

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FIGURE C6. END PLUG

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GENERAL ELECTRIC

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TITLE
END PLUG

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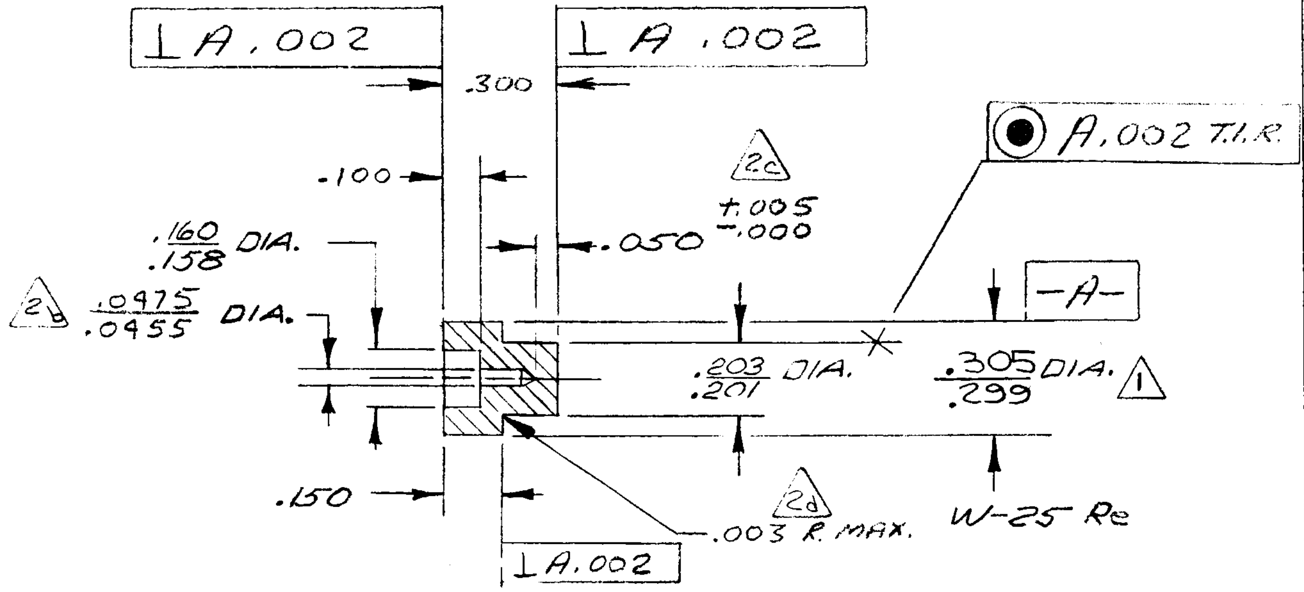

1. All W-25 Re to be to the following physical and chemical specifications:
   Density greater than 99.9% of theoretical.
   Leak rate less than 1×10^{-10} cc/sec on He M.S.
   Re content of 24 ± 1.5%
   No sigma phase particles larger than 15 microns in any dimension, no more than 5 particles larger than 5 microns in any area of 1 in. diam.
   In ppm; C<30, N<15, O<40, H<15, F<20, Al<15, Ta<300, Cr<15, Cd<100, Cu<15, Fe<70, Hf<75, Mo<200, Ni<15, Ti<15.

1 W-25 RE

NOTE:

UNLESS OTHERWISE SPECIFIED USE	APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS: FRACTIONS	DECIMALS	ANGLES
	145A5481	63 √	±	± .005	±

REVISIONS

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1	WAS .302/.300 DIA. E.M.L. 1-30-67; [illegible] 1-30-67; [illegible] 1-30-67	
2	a. DELETED P2 (TZM) b. .0475/.0455 WAS .096[illegible] c. ADDED +.005/−.000 TOL. d. ADDED .003 R. MAX. e. DELETED TZM NOTE f. ADDED ◎ & ⊥ 6-6-67 [illegible]; 6-7-67 [illegible]; [illegible] 6-7-67	

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FIGURE C7. END PLUG

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175A9426 CONT ON SHEET SH NO.	PELLET (TYPE I) FIRST MADE FOR NASA	CONT ON SHEET SH NO.
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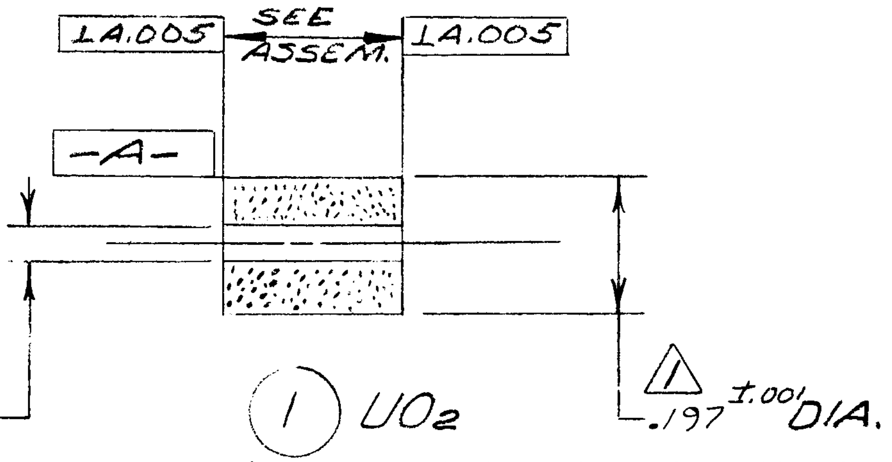

All UO_2 will have a bulk density of 95 ± 1% of theroretical density and a ratio of oxygen-uranium atoms of 2.005 ± .005. The UO_2 chemical specification is shown below:

Total Impurity Content <2500 ppm

Ca	<400 ppm
C	<100 ppm
Mg	<400 ppm
Si	<200 ppm
Fe	<200 ppm
Al	<150 ppm
Ni	< 60 ppm
Cr	< 35 ppm
Mo	< 25 ppm
Sn	< 15 ppm
Cu	< 10 ppm
Pb	< 5 ppm
Ag	< 1 ppm
Cd	< 0.5 ppm
B	< 0.25 ppm

Total Halides < 25 ppm

NOTE 1 Length/Dia. Ratio ≅ 2

UNLESS OTHERWISE SPECIFIED USE	APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS: FRACTIONS	DECIMALS	ANGLES
	145A5481	√	+ — −	+ — −	+ — −

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1	WAS .200 +.0005 -.0030	
	6-5-67 Linder 6-7-67 [illegible] 6-7-67	

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FIGURE C8. PELLET (TYPE I)

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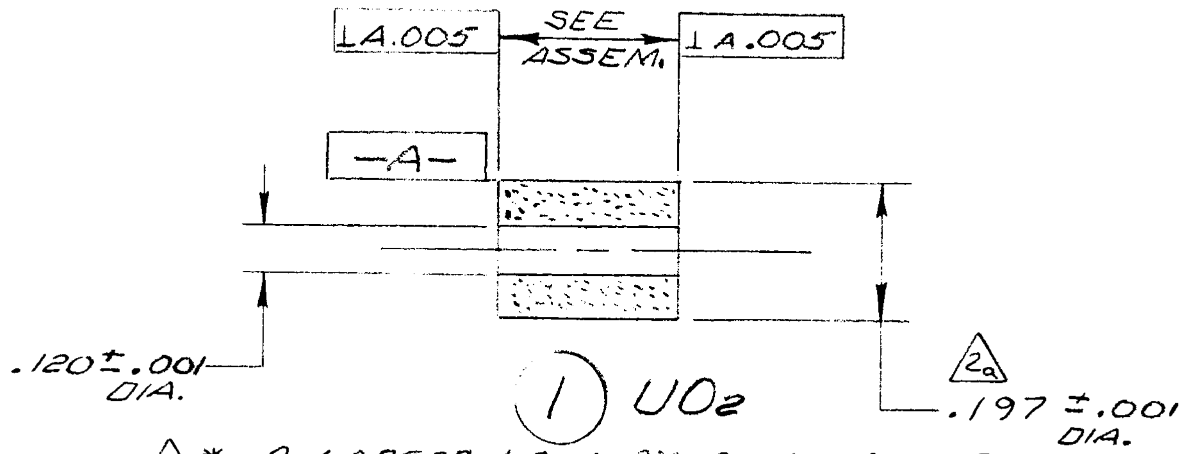

2b * A LARGER I.D. MAY BE EMPLOYED IF FABRICATION TECHNIQUES CAN BE DEVELOPED

All UO_2 will have a bulk density of 95 ± 1% of theroretical density ¢ a ratio of oxygen-uranium atoms of 2.005 ± .005. The UO_2 chemical specification is shown below:

Total Impurity Content <2500 ppm

Ca	<400 ppm	Mo	<25 ppm
C	<100 ppm	Sn	<15 ppm
Mg	<400 ppm	Cu	<10 ppm
Si	<200 ppm	Pb	< 5 ppm
Fe	<200 ppm	Ag	< 1 ppm
Al	<150 ppm	Cd	< 0.5 ppm
Ni	< 60 ppm	B	< 0.25 ppm
Cr	< 35 ppm		

Total Halides<25 ppm

NOTE 1 Length/Dia. Ratio ≅ 1 (1)

UNLESS OTHERWISE SPECIFIED USE	APPLIED PRACTICES	SURFACES	TOLERANCES ON MACHINED DIMENSIONS FRACTIONS	DECIMALS	ANGLES
	145A5481	√	±	±	±

REVISIONS		PRINTS TO
1	LENGTH/DIA. RATIO WAS ≅ 2 E. Mala 1-30-67 / 1-30-67 / H.E.S. 1-30-67	
2	a WAS .200 b. DELETED NOTE 6-5-67 Linder / 6-7-67 / 6-7-67	

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FIGURE C9. PELLET (TYPE II)

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